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OPERATIONAL PROBLEMS ASSOCIATED WITH HEAD-UP DISPLAYS DURING IN--ETC(U)
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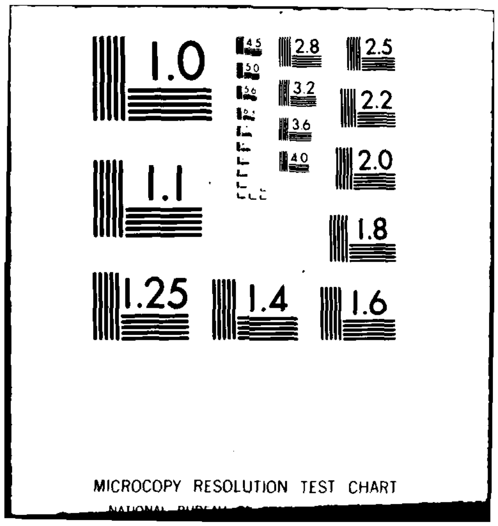
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Because of the interest in using head-up displays (HUDs) as primary flight references in instrument meteorological conditions (IMC), a survey of operational pilots flying HUD-equipped airplanes was undertaken. This survey revealed several problem areas that were common to most of the HUDs used. These common problem areas were: (1) the HUDs were too bright at night; (2) the field of view was too limited; and (3) the location of the design eye reference point does not correspond to the typical pilot practice of

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Item 20, Abstract (continued)

sitting as high as possible to maintain good visibility.

Other problem areas were reported, including: (4) the response of the HUD symbols is not adequately controlled by existing specifications; (5) pilots have an increased tendency toward disorientation while flying by reference to the HUD; (6) the instrument landing system (ILS) displays in use are not satisfactory; and (7) the balance between presenting necessary information and presenting too much is not always achieved on today's HUDs.

Concurrently with the review of operational problems, a review of HUD-related training was undertaken. This review shows that very little attention is being paid to initial and recurrent HUD training or to the development of HUD procedures for flight in IMC.

Several recommendations have been made to deal with these problem areas. Chief among these is the need for a coordinated flight/simulation experiment to develop design criteria for HUD symbol response and for the proper symbology for the ILS approach. These experiments would interact closely with the study of increased pilot disorientation with the HUD.

SUMMARY

In recent years, the head-up display (HUD) has been developed to provide aircraft flight data to the pilot in his view of the external real world. Originally developed for weapon aiming purposes, the HUD has become a flight reference used in routine instrument flight. An earlier study suggested that there are some operational problems unique to the HUD. To ascertain the magnitude of these problems, a survey of 280 pilots flying HUD-equipped airplanes was undertaken. Concurrently, a review of HUD training was also completed.

Several problem areas were noted in the pilots' responses to the survey of operational problems. Some of these operational problems were reported for most or all of the HUDs surveyed: inadequate dimming capability at night, limited field-of-view, and improper location of the design eye (usually too low). The last complaint usually described the design eye location as not representing the typical pilot practice of sitting as high as possible to obtain the best visibility, particularly in combat situations.

In addition to these comments which seem to apply across the board to all HUDs, the pilot responses also indicate that current HUD specifications do not adequately control the dynamic response of the display elements. A review of the present HUD specifications confirms that this issue is not addressed.

A disturbing result of the study was the reported increased tendency of pilots towards disorientation while flying by reference to the HUD.

The most common situation reported is while flying in-and-out of the clouds, although certain dynamic situations are also disorienting. Several hypotheses can be advanced at this time, but none are confirmed.

The instrument landing system (ILS) presentations on those HUDs with ILS modes are not satisfactory. The displays were usually described as "confusing" or "hard-to-fly." It is not clear whether the presence or absence of a flight director helps or hinders the ILS approach.

The pilots surveyed felt that the proper balance between displaying necessary information and too much was not always reached. They also cited a lack of adequate failure monitoring as a real concern. Several design recommendations can be made to improve the display of needed flight information on the HUD.

In addition to these hardware-related issues, the subject of training pilots to use the HUD and the procedures used while flying by reference to the HUD were reviewed. It was apparent that very little attention is being paid to initial and recurrent HUD training or to the development of procedures to use the HUD during routine instrument flight. In some instances strong negative organizational attitudes seem to discourage the pilots from using the HUD to its fullest capability.

A second problem revealed during this review of HUD training was the lack of training to explain the meaning of the velocity vector and how to control it during flight. Since the use of flight path angle as a control variable is not taught in any pilot training course, the new HUD pilot is forced to develop his own procedures during his first few hours of flying a HUD-equipped airplane. Although most pilots eventually learn to fly the display, it does seem that better initial HUD training will assist them to adapt faster.

Several issues remain unresolved. These critical issues, the dynamic response criteria needed, the problem of pilot disorientation, the presentation of ILS data, and the amount and type of data display, must be studied further and resolved in order to have adequate specifications for new HUDs. These issues all interact and an integrated experimental program must be developed. This will ensure that the next HUD will be a well designed HUD.

PREFACE

The work described in this report was conducted by Crew Systems Consultants under sponsorship by the Air Force Aerospace Medical Research Laboratory, Wright-Patterson AFB, Ohio under contract F33615-79-C-0521. Mr. Richard L. Newman served as principal investigator. Air Force project engineers were Major Michael F. Rundle and Mr. William L. Welde.

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ABBREVIATIONS

ACM	Air Combat Maneuvers
AFAL	Air Force Avionics Laboratory
AFB	Air Force Base
AFFDL	Air Force Flight Dynamics Laboratory
AFHRL	Air Force Human Resources Laboratory
AFM	Air Force Manual
AGARD	Advisory Group for Aerospace Research and Development
AIAA	American Institute of Aeronautics and Astronautics
ALPA	Air Line Pilots Association
ANG	Air National Guard
ANGB	Air National Guard Base
AOA	Angle-of-Attack
BA	British Airways
CAAC	Civil Aviation Administration of (Red) China
CAS	Calibrated Airspeed
CAT III	Category 3 Weather Conditions (i.e. RVR less than 1200 ft)
C-D	Clear Weather - Days
cg	Center of Gravity
C-N	Clear Weather - Nights
CPT	Cockpit Procedures Trainer
CRT	Cathode Ray Tube
Dash One	Air Force Flight Manual
DEFT	Display Evaluation Flight Test
DH	Decision Height
DME	Distance Measuring Equipment
EM	Electromechanical
E/M	Energy Management
ERP	Eye Reference Position (or Eye Reference Point)
FAA	Federal Aviation Administration
FOV	Field-of-View
FPA	Flight Path Angle
GS	Glideslope
HSI	Horizontal Situation Indicator
HUD	Head-Up Display
I&O	In-and-Out of Clouds
IAS	Indicated Airspeed
IEEE	Institute of Electrical and Electronic Engineers

IFALPA	International Federation of Air Line Pilots Associations
IFC	Instrument Flight Center (Air Force)
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
INS	Inertial Navigation System
IP	Instructor Pilot
JANAIR	Joint Army-Navy Aircraft Instrumentation Research
LAPES	Low Altitude Parachute Extraction System
MARS	Mid-Air Recovery System
McD-D	McDonnell-Douglas Company
mr	milliradian
NASA	National Aeronautics and Space Administration
NTSB	National Transportation Safety Board
PERSEPOLIS	Programme d'Etudes et de Realisation de Systemes Electroniques pour l'Organization et la Lecture d'Informations Synthetisees (Research and Development Program of Electronic Systems for the Display of Synthetic Information) - a French HUD project
PFPA	Potential Flight Path Angle
PWA	Pacific Western Airlines
RAE	Royal Aircraft Establishment
RAF	Royal Air Force
RAG	Replacement Air Group
RVR	Runway Visual Range
SAE	Society of Automotive Engineers
SETP	Society of Experimental Test Pilots
SI	Solid Instruments
SNPL	Syndicat National des Pilotes des Lignes (French ALPA)
TACAN	Tactical Air Navigation (system)
TAS	True Airspeed
TFG	Tactical Fighter Group
TFW	Tactical Fighter Wing
UHF	Ultra High Frequency
UK	United Kingdom
UPT	Undergraduate Pilot Training
USAF	United States Air Force
USMC	United States Marine Corps
USN	United States Navy
UTA	Union de Transports Aeriens (a French airline)
W/D	Weapons Delivery
VAM	Visual Approach Monitor
VFR	Visual Flight Rules

VHF	Very High Frequency
VMC	Visual Meteorological Conditions
VOR	VHF Omni-Range (navigation system)
VTOL	Vertical Take-Off and Landing

BACKGROUND

HISTORICAL HUD DEVELOPMENTS

The head-up display (HUD) is an outgrowth of the reflective gunsight of World War II. In such gunsights, the aiming symbol was generated as a beam of light, projected upwards from the top of the instrument panel and reflected towards the pilot by a semitransparent mirror placed in his view through the windshield. If the design is correct, the pilot will see the symbol "floating" in his view of the outside scene. There are several advantages to such a reflecting gunsight over conventional iron sights. First, the aiming symbol can be moved to compensate for the range, drift, acceleration factors, and rate of target closure. Second, the image of the aiming symbol can be focused to form a virtual image lying in the same plane as the target. This minimizes the pilot's need to accommodate and focus on two distances simultaneously. In addition, having a virtual image lying in the same plane as the target eliminates paralax errors. Finally, the brightness of the aiming symbol can be varied to allow for changes in ambient light levels.

It takes no great amount of imagination to see the next step in the development of the HUD - the addition of flight information to the virtual image. In fact, this can be our working definition of a head-up display: a cockpit display that presents flight data in the form of a virtual image in the pilot's view of the real world. The inclusion of flight data disqualifies simple reflecting gunsights. The requirement

for a virtual image eliminates such devices as angle-of-attack indexer lights or peripheral cues such as moving barber poles. As useful as these non-optical devices may or may not be, they are to HUDs what an iron gunsight is to a lead-computing reflecting gunsights. Most such devices should be called peripheral cues, not HUDs.

Much of the early development of head-up displays took place at the UK's Royal Aircraft Establishment (RAE) in the late 1950s and early 1960s. Naish, in particular, led these developments at the RAE(1,2,3). He continued his HUD developments with Douglas Aircraft in the late 1960s(4). The British approach was to use a HUD equipped with a single horizon line and aircraft symbol using the flight director computer to drive the aircraft symbol to guide the pilot during instrument flight. In most HUDs of this type, the airspeed and altitude were shown digitially, although some used error cues for airspeed or ILS deviation. The British school suggested that a HUD symbology need not be conformal to the real world, but rather that only an approximate overlying of symbols and real world cues was required(5). Most of these conclusions were based on extensive flight testing in both simulators and airplanes. The success criteria for most experiments was for the minimum tracking error - the ability of the pilot to self-monitor (i.e., to crosscheck) was not considered, although Naish did purposely misguide some subjects to a touchdown not on the runway and found that they did tend to ignore the HUD and fly the simulated real world cues as soon as they became available(6).

Part of the reason for the conclusion that a conformal HUD was not required may have been the feeling that the ability of airborne equipment to generate a contact analog display was lacking at the time(7). Another conclusion drawn was that a 1:1 scaling in pitch did not necessarily give

the minimum pilot workload(8). This has carried forward to the AV-8 (Harrier) and the F-14 (Tomcat) HUDs which use 5:1 and 4:1 scaling in pitch today.

In the mid-1960s, additional work was being carried on in the USA, chiefly by Sperry under Navy support. This work, led by Gold, emphasized two facets of HUDs: the use of the display in visual landing approaches and the necessary optical qualities of the display. This work concluded that, for the visual approach, a single directed cue which the pilot would fly to the touchdown point was superior to a combination of velocity vector and target glideslope scale(9). This same conclusion has been reached in subsequent studies(10,11). The difference between these visual approach techniques and the previous, "British school" techniques lies in the data processing. The early studies provided a left/right, up/down guidance cue from a conventional flight director computer, while the visual approach work provides guidance from the pilot flying the airplane to place a symbol over the runway end. By an appropriate feedback computation, this latter method will guide the airplane to a desired flightpath. (It is not absolutely necessary to have visual contact with the runway; a synthetic runway location on the HUD will suffice.)

The other studies by Gold and his co-workers dealt with the optical characteristics of the HUD. These included the appropriate field-of-view required in a display and the allowable visual disparity between the views from each of the pilot's eyes(12,13,14).

In addition to the two approaches to HUD symbology - the symbolic or flight director school (the British school) and the visual landing guided flight path school - there is a third technique, the contact analog or realism school. This approach was advocated by a number of

workers in both head-up and head-down displays. Several HUD formats using contact analog presentation were developed by Bergstrom(15), Carel(16), Gallaher, et al.(17), and Wilckens(18). The Air Line Pilots Association (ALPA) has also recommended a contact analog format(19). The only HUD using a contact analog format in use today is the Thomson TC-121/-125 developed by Klopfstein(20).

In the mid-to-late 1960s, the HUD concept was developed to the point that it could be included in the weapon delivery systems of military fighters. The first two significant US aircraft to use head-up displays were the A-7D/E (Corsair II) and the AV-8A (Harrier). Both of these aircraft were single-seat attack aircraft. In both cases, the driving rationale for using a HUD was to upgrade the gun/bombsights used in previous attack airplanes.

These two HUDs differ from one another in their presentations. The AV-8A HUD is a direct outgrowth of the early British approach to head-up displays. Aside from its VTOL mode, the AV-8A HUD is quite similar in format to the Smiths Industry HUDs shown in Reference 7. The primary symbol is an "aircraft symbol" which indicates the pitch attitude. The pitch and heading scales are compressed from the real world by a factor of 5:1 as was mentioned above.

The Elliott HUD used in the A-7D/E cannot be said to belong to any of the schools of HUD design described above. The basic symbol in the HUD is a velocity vector which is derived from an inertial platform. While the horizon and pitch references are conformal with the real world horizon, the display cannot be said to be a contact analog. The use of a true flight path indicator and a pitch scale reference eliminates it from the visual approach school and the dependence on true alignment of

the velocity vector (flight path reference) and the real world eliminates the A-7 HUD from belonging to the British school of HUD design. The availability of an inertial platform plus the computational ability of the A-7's weapons computer was not considered in the early development of head-up displays. Perhaps this should indicate the fourth type of HUD - the conformal symbolic HUD.

Since the introduction of the head-up display in the A-7D/E and AV-8 aircraft, HUDs have been used on A-10, F-14, F-15, F-16, and F-111 fighter aircraft and on the JC-130 and CH-3E mid-air retrieval aircraft. These last two types are used for recovery of parachute packages where the HUD helps the pilot maintain a constant sight picture when the horizon is obscured by clouds or haze(21).

POTENTIAL FOR ALL-WEATHER LANDING

The head-up display has been suggested as an aid to alleviate some of the problems faced by pilots during a landing approach under adverse weather conditions. These problems, although known to pilots for some time, were analyzed by the Australians Lane and Cumming in the 1950s(22,23). They studied the visual cues used by pilots during final approach to landing and concluded that a suitable visual aiming device could be used to assist the pilot in judging his approach.

The Lane and Cumming study(22) was primarily concerned with the problems of the pilot in judging his final approach path in visual meteorological conditions (VMC), although they did discuss the effect of night or weather in obscuring the cues. The cues most widely used by pilots were the relative angle of the touchdown point below the horizon, the shape of the runway or runway light patterns, and the "center of

expansion." Naturally some of these cues are greatly affected by night or reduced visibility.

Other researchers have amplified on these cues or their absence. Carroll(24) and Swartz, Condra, and Madero(25) described the deterioration in these visual cues during low visibility landings. In general, the perception of errors in the vertical plane is much more critical than the perception of errors in the lateral plane. This same point was made in the National Transportation Safety Board's study of approach and landing accidents(26).

Kraft and Elworth(27) studied the effect of night visual approaches in a simulator study and found that the slope of the terrain and the distribution of lights in front of or behind the airport had a strong effect on the visual glidepath actually flown by pilots.

At this point we should separate the two specific problem areas: (1) the visual approach, and (2) the transition from instrument meteorological conditions (IMC) to a visual landing. During a visual approach, the pilot's problem is to fly a stabilized approach on a safe glidepath - usually of the order of three degrees. Because of varying and often misleading cues, such as described by Kraft and Elworth, he can be misled into flying a dangerously low flight path. (While the opposite problem, flying too high an approach can occur, it is not as critical for obvious reasons.)

The IMC transition to a visual landing has some of the same problems; however the problem here is not flying a safe flight path down to the landing flare, but flying the flare itself. On final the pilot is flying head-down using his panel instruments. Upon reaching visual contact, he must come head-up and complete the landing visually. If any

illusions are present, and some usually are during low visibility conditions, the pilot can be led by these illusions into error. The problem is compounded by the very short time interval between ground visual contact and touchdown. This short interval makes it difficult to assess the direction of the flight path. the velocity vector. In addition, the foreshortened visual segment can be perceived as an aircraft pitch up.

As a result of these problems, the head-up display has been suggested as a viable aid for the landing task. Most HUD discussions to date have concentrated on either the visual approach task or the instrument-to-visual transition task. During visual landings, the HUD could provide visual guidance augmentation, as described by Gold(9). Such a HUD has been tested in simulated night visual approaches(28) and has been used operationally by an airline flying in arctic "whiteout" conditions(29). The simulated approaches showed a large increase in flight path precision with a simple, single cue HUD.

On the other hand, the flight director philosophy of the British school would be of help primarily during instrument approaches. By placing flight data - flight director, airspeed, and altitude cues - in the pilot's windshield, the transition to purely visual flight should be enhanced. In theory, the dual data field of view should make the transition easy by allowing the pilot time to assess the real world cues without giving up the instrument cues. Since the flight director and other cues were not conformal, no velocity vector data were presented to assist the pilot in the flare. This type of HUD has been extensively tested, both by the RAE(1,2,3) and in the USA(4,30,31). It has also been operationally tested in a business jet operated by NABISCO(32).

The civil transport pilot organizations, notably the US Air Line Pilots Association (ALPA) and their French counterparts (SNPL), have been quite vocal in their insistence on having head-up displays installed on transport airplanes(19,33,34). Usually the type of HUD desired by these air line pilots has been of the contact analog type. The benefit of the contact analog display is not clear since it would provide the same cues as the real world cues, although without the extra visual illusions caused by terrain slope, missing horizon, etc. In any event, the ALPA position has been supportive of the concept of a contact analog display, but has provided little data to support this particular HUD format.

Evidence that a head-up display can be valuable in improving landing safety is demonstrated by the threefold reduction in carrier landing accidents attributed to the A-7E HUD(35). There is also a tenfold reduction in the night carrier takeoff accident attributed to this HUD.

Finally, a joint NASA/FAA program was begun in 1977 in an effort to ascertain the extent of benefits and problems resulting when a HUD is used for the low-visibility landing. To date these studies have been confined to laboratory measurements and to ground-based simulations. The thrust of the studies has been cognitive switching, that is, the ability of the pilot to deal with data from two separate data fields which happen to be superimposed. Haines(36,37) gives an overview of these HUD studies.

The NASA studies did examine the ability of the pilot to resolve differences between the HUD and the real world cues. In general, the pilots tended to follow the runway cues as they became available(38). Of possible concern, however, this same study noted that the subject pilots took much longer with the HUD to see an obstruction on the runway than

without the HUD. In some cases, the subject pilot using the HUD did not perceive another airplane taxiing on the runway at all.

PRESENT DAY OPERATIONAL HUDs

At the present time, head-up displays are in operational use in many aircraft - predominantly fighter/attack airplanes. In the US inventory, HUD-equipped fighters include the A-7, A-10, AV-8, F-14, F-15, F-16, and F-111 aircraft. The F-18, soon to be introduced, will also have a head-up display.

In addition to these fighters, two special purpose aircraft, the JC-130 and CH-3E MARS aircraft have been retrofitted with a HUD to assist in the mid-air retrieval of parachuted packages. These HUDs were designed to assist the pilot during his pass to the parachute thus ensuring proper positioning - particularly when the horizon is obscured. At the present time, the JC-130 HUDs are operational. The CH-3E MARS helicopters no longer have a recovery mission and the HUDs and other related equipment have been removed.

Several civilian operators have equipped their transports with HUDs for operational use. For the most part, these HUDs have been intended for assistance with the visual landing approach. Pacific Western Airlines (PWA) is the major civil user of HUDs. PWA uses a Sundstrand Visual Approach Monitor (VAM) for guidance in landing approaches to remote arctic airports. Because of the combination of lack of visual contrast and the absence of ground based aids, the VAM is considered essential to the arctic operations. PWA has installed the VAM on Boeing 727 and 737 airplanes and on Lockheed L-100 (civil version of C-130) airplanes. The VAM is also installed in Hawker-Siddeley Trident airplanes operated in

airline service by the Civil Aviation Administration of China (CAAC), the People's Republic of China.

The only civil use of HUD in instrument flight is by Air Inter, the French domestic airlines. Air Inter has installed Thomson-CSF HUDs on board its Dassault Mercure airplanes to aid in category 3 (CAT III) instrument landings. These electromechanical HUDs are used to monitor the autoland system and are not the primary approach aid. However, below fifty feet, the pilot has the option of completing the landing using the HUD if the autoland system disengages. Air Inter operates the Mercure to minimums of 25 ft decision height (DH) and 125 m runway visual range (RVR). After several thousand category III landings, Air Inter has had ten instances of autoland disconnect below fifty feet with a landing completed using the HUD. They have had no reported instances of HUD failure following equipment self test just prior to the approach.

Future civil transports with HUDs include the McDonnell-Douglas DC-9-80 which is being certified at present and the Boeing 767 which is still in the development stage. British Airways will have HUDs installed in their Boeing 737 aircraft to provide takeoff run steering guidance.

Table I lists Civil HUDs and US Military HUDs that can be considered to be operational equipment. In addition to these HUDs, there have been many displays in the prototype stage or which have been used in operational evaluation. Specific display characteristics will be discussed in a later section.

OPERATIONAL PROBLEMS WITH HUDs

Because of the successes that the few operational HUDs have enjoyed, primarily as weapon aiming devices, HUDs have been promoted as panaceas

AIRCRAFT	HEAD-UP DISPLAY	MISSION	OPERATOR
A-7D/E	Marconi-Elliott AN/AVQ-7(V)	Attack	USAF, USN
A-10	Kaiser	Attack	USAF
AV-8	Smiths Industries	VTOL Attack	USMC
F-14	Kaiser AN-AVA-12	Fighter	USN
F-15	McDonnell-Douglas	Fighter	USAF
F-16	Marconi-Elliott	Fighter	USAF
JC-130	Sundstrand MARS-HUD	Mid Air Retrieval	USAF
C-130	Sundstrand VAM	Visual Landing Aid	PWA
B-727	Sundstrand VAM	Visual Landing Aid	PWA
B-737	Sundstrand VAM	Visual Landing Aid	PWA
DC-8	Sundstrand VAM	Visual Landing Aid	UTA
Trident	Sundstrand VAM	Visual Landing Aid	CAAC
Mercure	Thomson CV-193M	CAT III Landing	Air Inter
	The following HUDs are in prototype testing.		
A-10	Kaiser	Night Attack	Fairchild
AV-8B	Smiths Industries	VTOL Attack	McD-D
F-18	McDonnell-Douglas	Fighter/Attack	USN
DC-9-80	Sundstrand	All Purpose	McD-D
	The following HUDs have been operationally evaluated.		
CH-3E	Sundstrand MARS-HUD	Mid Air Retrieval	USAF
Falcon	McDonnell-Douglas	Executive Jet	Nabisco
C-130	Sundstrand VAM/LAPES	LAPES	USAF, CAF
Several	Sundstrand VAM	Visual Landing Aid	Several
Several	Thomson CV-91	Visual Landing Aid	Several
	The following HUD is planned for production.		
B-737	Sundstrand VAM Adaptation	Takeoff Guidance	BA
	The following HUDs have been tested inflight.		
Nord	Thomson TC-121	ILS Landing Aid	Thomson
DC-9	McDonnell-Douglas	ILS Approach	McD-D
DC-9	Elliott	ILS Approach	McD-D
CL-84	Sperry	VTOL Landing Aid	USN
T-38	Sundstrand Lightline	Visual Landing Aid	USAF
CV-880	Singer (Thomson) L-193	Landing Aid	FAA
CH-3	Singer (Thomson) L-193	Mid Air Retrieval	USAF
DC-7	Bendix Microvision	IMC Landing Aid	FAA

TABLE 1

OPERATIONAL HEAD-UP DISPLAYS IN CIVIL AND U. S. MILITARY SERVICE

for most of the instrument approach and landing problems facing the pilot. The literature is full of glowing testimonials about the apparent advantages of head-up displays over conventional head-down panel instruments. Unfortunately, few of the reports and articles in the literature describe operational (as opposed to test programs) experience with a HUD. Even the few operational evaluations have been conducted with pilots who were well motivated in the use of HUDs.

Although most military HUDs were not developed for routine instrument flight, as the pilots became more confident in their use, both USAF and USN pilots began to use the HUD as a flight reference during flight in IMC. This was done on an informal basis with little or no guidance from either the aircraft flight manual or from the instrument flight publications (Air Force Manual AFM-51-37(39)).

In 1976, two Air Force Commands, Tactical Air Command and Aerospace Defense Command, requested guidance from the Air Force Instrument Flight Center (IFC) on the techniques for using head-up displays during flight in instrument conditions. At that time, very little definitive data existed to develop a standardized set of HUD techniques suitable for inclusion in instrument flight handbooks. (The same statement applies today.)

In response to this request, IFC undertook to conduct a survey to determine the degree that HUDs were used during instrument flight by 123 USAF pilots and the problems encountered by these pilots while using HUDs in IMC. This survey was conducted among pilots flying A-7D, F-15, and F-111 aircraft. The conclusions, reported by Barnette(40), are

> The majority of the pilots surveyed stated a cross-check with the instrument panel was constantly required; therefore, HUDs are not being used as a totally primary flight reference system.

None of the HUDs covered in this survey possessed an adequate failure monitor system. Erroneous information could be displayed without the pilot's knowledge unless a constant instrument panel cross-check was maintained.

All flight information is not available on the HUDs. Examples of missing information include TACAN, DME, bank scales, and engine information.

A potential problem appears to be the distracting and sometimes disorienting effect, due to constantly changing external visual environment, of flying the HUD in IMC.

In addition to the problems associated with the HUD itself, there is scarce information regarding techniques and procedures for the use of the HUD in IMC. The majority of surveyed pilots use either the all-weather section of their Dash-One and/or the standard instrument procedures contained in Air Force Manual AFM-51-37. Neither of these documents deal specifically with IMC HUD flying; therefore, the procedures, techniques, and instructional methods are not standardized for HUD flying.

Although HUD symbology has become fairly standardized for use as a weapons delivery system, standardization for use as a primary flight reference is still lacking. Without procedures and techniques, instructional methods cannot be established and published. Extensive research is required to determine if the HUD can be used as a primary flight reference system. In the absence of this research, the full potential of head-up display may never be realized(40).

As a result, Barnette urged that a pilot factors program be started to determine: (1) whether HUDs are appropriate to use as a primary flight reference system, (2) what symbology and format are required for the HUD to be used as primary flight reference, and (3) what procedures and techniques should be developed for the HUD under IMC.

Barnette's survey raised several questions that had not been addressed in previous HUD tests, for example, the lack of an adequate failure detection scheme within any HUD examined, the absence of required data in the display, an increased tendency towards vertigo when flying the HUD in IMC, and a lack of standardization in HUD symbologies and in HUD procedures. Subsequently a second questionnaire was prepared in

early 1978 and circulated to pilots flying HUD-equipped A-7D, A-7E, A-10, AV-8, CH-3, F-14, F-15, F-16, F-111, JC-130, and civil B-737 airplanes(41). This questionnaire attempted to further define some of the problem areas noted by Barnette. The analysis of this questionnaire is the subject of a later section of this report.

In addition to these two IFC-sponsored surveys, an earlier Air Force Avionics Laboratory (AFAL) sponsored study(42) interviewed 17 A-7D pilots in an effort to ascertain pilot problems with that HUD. This survey was primarily concerned with weapons delivery and not specifically with instrument flight. Nevertheless, most of its questions and responses have their counterpart in the present survey. The only question/responses not included in the present survey dealt with the point of reference of the HUD display - should it be centered on the flight reference line, on the armament datum line, on the velocity vector, or located at the center of the display? The overwhelming response (14 replies) was "velocity vector." One pilot chose the flight reference line. No pilot chose the armament datum line or the center of the display. As will be seen later, this same choice is being made for the revised F-16 HUD symbology.

To summarize, the use of the modern HUD in instrument conditions has produced several problems. These operational problems do not, in many cases, agree with test data, often done in simulators with well-motivated subjects. The success of these operational HUDs varies widely because of some of these operational problems, which do not appear to be addressed in current HUD specifications or in published HUD research.

HUD TRAINING ASSESSMENT

Difficulties with pilots learning to use HUDs were noted during two recent evaluations(21,43,44). Extensive learning variations among pilots were observed. The original thought in each of these flight tests was to give each subject pilot (already qualified in the mission and aircraft) a one hour familiarization with using the HUD. During the testing, some pilots adapted quickly to the HUD while others learned more slowly. There does not appear to be any correlation between the learning rate and previous experience or final performance using the HUD. Two points must be made regarding this learning time. First, it seems to be more attitude-related than either ability- or experience-related. Second, most pilots during these test programs flew more precise patterns while learning to use the HUD than without the HUD.

In spite of the popular support for HUDs, most HUDs do not appear to be entirely self-explanatory to a pilot new to the concept. Pilots have difficulty in learning how to use the HUD properly. Yet, based on informal discussions with military and civilian training cadres, only the French airline Air Inter appears to expend much effort in teaching the pilot how to use the HUD.

One problem, observed in the HUD tests described above, was "HUD fixation." This is the tendency for the inexperienced (to HUDs) pilot to concentrate on the display to the exclusion of the real world cues. One pilot during the mid-air retrieval evaluations said that he was "too busy looking at the HUD to look outside."

The difficulty of monitoring HUD data was confirmed during the JC-130 MARS evaluation(44). During portions of this testing, an intentional error was introduced into the HUD computer. The resulting display,

if followed, would have caused the pilot to fly the airplane into the parachute. The test was intended to determine if the pilot could recognize his abnormally low approach and fly the real-world cues which were in conflict with the HUD data. During the twenty-five passes in this test, three parachutes were struck, compared with no strikes in over 400 passes with the normal HUD display. The significant point is the apparent inability of the pilot using the HUD to detect these subtle errors in the displayed data. By comparison, during the CH-3E evaluations recovering parachutes in Southeast Asia, the pilots reported apparent conflicts between the real-world cues and the HUD cues. In this case, they also chose to follow the HUD display and were successful in their recoveries. The discrepancies here were caused by visual illusions(43).

The problem is compounded by the simulator data showing that pilots will fly the real-world cues when any discrepancy appears(6). Obviously there is a fundamental difference between simulated experiments and operational flying (even operational testing). The underlying problem is how to train the pilot to detect the failure. This has been pointed out in the operational surveys conducted by IFC, but has not been addressed by either hardware or crew training.

Other procedural problems exist with the use of HUDs. One of these reflects the ability of the HUD to present flight path data to the pilot. Historically, we have not had the means of presenting flight path data, γ, to the pilot.* As a result all pilot training has dealt with the indirect control of γ by using pitch and power to control airspeed and vertical velocity. When told to fly using the velocity vector on the HUD, the

* The terms "flight path angle," "velocity vector," and the symbol γ all refer to the angle that the airplane's trajectory makes with the horizontal.

pilot must sort out the relationships between flight path angle, angle of attack, pitch attitude, airspeed, power, and vertical velocity. The problems arise when the pilot does not have a clear understanding of these relationships or has not had time to sort out the new techniques.

These issues were addressed in a paper presented at the International Head-Up Display Symposium, held in Vancouver(45). To this point, the training and procedural issues involved with HUDs have not been addressed. Those specific problems that have been identified include: (1) learning variations, (2) HUD fixation, (3) procedures/training to permit detection of HUD malfunctions, (4) training to allow the pilot to choose the proper course of action between two conflicting data sources, (5) training to ensure that the pilot understands the principles behind the data, and (6) development of appropriate techniques to fly the airplane using this data. To this end, an effort has been made to review HUD training as it exists within the Air Force at this point in time.

HUD SURVEY

Following Barnette's report in 1976(40), many new issues were raised, among these was the question of pilot vertigo induced by the use of a HUD. Discussions at the International Head-Up Display Symposium held in September 1977(46) failed to resolve these issues and reinforced the lack of understanding of the use of HUDs in day-to-day operational flying. As a consequence of these discussions, Newman prepared a second questionnaire(41) to be circulated by the Instrument Flight Center (IFC) to address these issues. A copy of this questionnaire is attached as Appendix A.

PROBLEMS ADDRESSED

The problems addressed by this questionnaire w

- Problems perceived by pilots in various flight conditions
- Degree of use of the HUD related to weather and phase of flight
- Pilot confidence in the HUD
- Symbology problems
- Stability/accuracy issues
- Tendency towards vertigo/disorientation
- Optical problems (including brightness)
- Clutter
- Training or procedural issues
- The data desired in a general purpose HUD.

In addition, the questionnaire asked basic questions regarding experience and pilot qualifications. It also included a special section for those pilots who had flown other HUD-equipped aircraft. This section asked for a preference between the HUDs flown, the reasons for the preference, and inquired if previous HUD experienced helped or hindered the transition to a new HUD.

PILOTS SURVEYED

The pilots surveyed were primarily military operational (as opposed to test) pilots. These included pilots flying A-7D, A-7E, AV-8, A-10, F-14, F-15, and F-111 fighter aircraft. The reason for separating A-7D and A-7E pilots was an effort to distinguish between Air Force (A-7D) and Navy (A-7E) trained pilots.

In addition, questionnaires were sent to pilots flying CH-3E and JC-130 MARS aircraft equipped with HUDs. Unfortunately, by the time the questionnaires were sent, the CH-3E MARS mission had been terminated and no HUD-qualified pilots were available. The JC-130 unit elected not to participate in the survey; however they did forward a set of subjective comments made during initial testing of the units.

Questionnaires were also sent to military test pilots flying F-16 and A-10 fighters and to RAF pilots flying HUD-equipped airplanes at RAE-Bedford. Thirteen F-16 and two A-10 pilots responded. No replies were received from the British pilots. The A-10 test pilot replies were included with the A-10 operational pilot responses. The F-16 responses were used "as received."

Questionnaires were also sent to civilian transport pilots flying the Sundstrand VAM on Boeing 727 and 737 and Lockheed L-100 (C-130)

transports. Only two B-737 pilots responded. Questionnaires were also forwarded to the French to circulate among pilots flying the Thomson 193M HUD in CAT III weather. Because of language difficulties, no formal responses were obtained, although some verbal replies were forwarded via FAA personnel. The civilian transport data were a low priority area in this study.

Table II shows the replies received together with the experience levels of the pilots. Aside from the A-7E and the F-16, the experience levels for the fighters are representative. The A-7E, F-16, and B-737 experience levels are higher than average. (The B-737 replies are typical for airline captains.)

RESPONSES RECEIVED

The questionnaire will be reviewed and the answers cited in the various tables. For ease in reading, all of the remaining tables in this section will be found collectively at the end of the section.

Degree of Use of the HUD

The answers to the question "How do you routinely use the HUD under the following weather conditions and phases of flight?" are listed in Table III. While this question did ask for day/night differences, very few pilots answered with other than check marks. As a result, no differences between day and night operations can be discerned. If a pilot did indicate day versus night, only the day checkmark was used.

Operational Problems

The question as stated was "What problems have you encountered when using the HUD in the following weather conditions?" The replies are listed in Table IV and are listed by aircraft type and by the flight

AIRCRAFT	NUMBER OF REPLIES	TOTAL FLYING TIME(Hrs)			TIME IN TYPE(Hrs)		
		Low	Median	High	Low	Median	High
A-7D	92	330	1850	5655	25	400	1700
A-7E	19	1160	2000	2800	850	1100	1900
A-10	25	350	1700	4100	50	150	500
AV-8	25	425	1800	4600	75	500	1100
F-14	14	300	1200	3000	15	150	1000
F-15	50	350	1700	4000	31	300	700
F-16	13	1500	3300	4700	11	140	700
F-111	40	300	1800	4500	50	820	1550
VAM	2	15000	16500	18000	3000	3750	4500
Total Replies: 280							

TABLE 2

EXPERIENCE DISTRIBUTION

OF PILOTS RESPONDING TO

HUD QUESTIONNAIRE

conditions: Solid Instruments (SI), In-and-Out of Clouds (I&O), Clear Weather - Days (C-D), and Clear Weather - Nights (C-N). All of the answers were made in the respondents' own words. The responses were not prompted by further questions since, presumably, the pilot had not looked inside the questionnaire at this point.

The replies were collected under a set of standard headings based on interpreting the replies.

Symbology Problems

The pilots were asked "Are there any format problems, such as distracting symbology, poor sensitivity, 'backwards' cues, distortions, etc?" The responses to this question are shown in Table V.

Vertigo/Disorientation

The replies to the question "Have you noticed any tendency toward vertigo or disorientation?" are shown in Table VI. In a similar fashion to the previous section, the degree of use during descents is also shown with one point for primary use of the HUD and one-half point if it is used, but not as primary.

Optical Problems

Three optical questions were asked, not counting the question of distortions in the previous section on symbology. The first of these optical questions was "Has the HUD produced any eye discomfort?" Very few pilots answered in the affirmative. Those that did usually indicated that brightness was the problem.

The second question was "Is the brightness control adequate for all weather conditions?" Many pilots who answered "no" also made comments indicating the reason for the "no" vote. A related question, "Can you

control the brightness to make the entire display comfortable to use?" was intended to determine if the uniformity of the brightness across the display was satisfactory. However, it appears that the respondents interpreted the question identically to the previous question. Because of this apparent misinterpretation, the replies should be carefully considered.

The replies to these three questions, plus any optical-related replies to the symbology question are shown in Table VII.

Stability/Accuracy Issues

The intention of this question was to ascertain the accuracy of the HUD system in positioning the symbols and to determine if any inaccuracies were severe enough to be a problem. The question as written, however, asked if the velocity vector pointed to the runway. While this did not answer the issue desired, it is still valuable data.

The question was "Does your velocity vector or flight path marker always line up over the runway on approaches?" and "Does this cause any problems during routine instrument flying?" The replies to these questions are shown in Table VIII along with an indication of the amount of use the pilot makes of the HUD during landing approaches. The index of use of the HUD was chosen as one point for every pilot using the HUD as his primary flight reference during approaches and one-half point if he uses the HUD, but not as the primary flight reference.

Clutter

The replies to the question, "Is the HUD ever too cluttered?" are shown in Table IX. Other related questions are found with the other symbology replies in Table V.

Pilot Confidence in the HUD

Two questions were asked of the pilot: "Do you feel that the HUD is more, equally, or less accurate than panel instruments" and "Do you feel that the HUD is more, equally, or less reliable than panel instruments?" The answers to these two questions are shown in Table X.

The Data Desired in a HUD

The pilots were presented with a list of data display items and asked to select the ones desired in a "general purpose HUD" for routine instrument flying. The responses are summarized in Table XI.

In addition, many pilots offered general comments. Where appropriate, these remarks were incorporated into the replies for specific questions.

Two questions forced the pilot to decide what data he wished to have deleted from or added to his HUD. The specific questions were "If one data display had to be deleted from your aircraft's HUD, which would you choose?" and "If one additional data display could be added, what would you choose?" The answers to these questions are shown in Tables XII and XIII.

Training and Procedural Issues

Three separate issues were raised in the questionnaire. The first dealt with the subject of initial training in the use of the HUD. The question was "Was your initial HUD training adequate?" Comments were also solicited. The replies to the specific question are tabulated in Table XIV, with the comments listed in Table XVI.

A second question dealt with the published procedures: "Are the published procedures (AFM-51-37 or Dash One) adequate and appropriate for

HUD flying in all weather conditions?" Again, comments were solicited. The replies to the question are also shown in Table XIV with the comments dealing with procedural issues shown in Table XVII.

The third issue raised was the suitability for HUDs in undergraduate pilot training (UPT). The replies to this question, "Do you feel that a good, all-purpose HUD would help in primary flight training or in initial checkout in a new airplane?" are also shown in Table XIV. Many pilots qualified their answers because of apparent concern over the UPT student becoming overly dependent on the HUD. These qualified replies are shown as well.

A fourth training issue was asked of those pilots who had had experience in flying other HUD-equipped airplanes. They were asked if having previous HUD experience helped or hindered their adaptation to a new HUD. These replies are shown in Table XIV also.

Previous HUD Experience

Pilots were asked if they had flown other HUD-equipped airplanes. Those that had were asked to identify the aircraft/HUD and state a preference (with reasons). They were also asked to indicate if previous HUD experience helped or hindered transition to a new HUD. The replies to these questions are listed in Table XV.

General Comments

Constructive remarks of a general nature that could not easily be fit in elsewhere are listed in Table XVIII.

ADDITIONAL QUESTIONNAIRES

Several pilots were asked to complete these questionnaires a second or third time. These pilots included A-7 pilots of the 178th

Tactical Fighter Group (TFG), Ohio Air National Guard (ANG) who were observed over a period of time during their first year in the A-7D. Only one questionnaire from these pilots was used in the tabulation - the most recent response (with the highest time flying HUDs). The previous questionnaires are only used to show changes in perception and attitude during the initial period flying HUDs. This will be covered in a later section of this report. Additional questionnaires were sent to those F-16 pilots who flew the European test tour. This was done to see if the original comments on the ILS display would be changed as the pilots obtain more weather experience. The original comments were chiefly based on tests conducted at Edwards AFB (in good weather) and the pilots did not have much experience in flying ILS approaches in weather. To date, these responses have not been received.

While no questionnaires were received from the French airline pilots, they did forward the observation that their pilots did experience vertigo particularly when making instrument approaches in the early morning hours at dawn.*

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* Forwarded via Joe Cox, FAA Headquarters, June 1979.

WEATHER	PHASE OF FLIGHT	AIRCRAFT AND HUD[a]																															
		A-7				A-10				AV-8				F-14				F-15				F-16				F-111				VAM			
		PR	U	OC	NU	PR	U	OC	NU	PR	U	OC	NU	PR	U	OC	NU	PR	U	OC	NU	PR	U	OC	NU	PR	U	OC	NU	PR	U	OC	NU
Solid IMC	Climb	46	43	5	2	-	12	28	48	36	36	28	-	-	14	50	36	40	34	18	4	54	38	-	-	-	18	35	45	-	-	-	100
	Cruise	41	41	16	2	-	12	32	56	60	36	4	-	-	21	50	29	34	46	18	2	62	31	-	-	-	32	32	32	-	-	-	100
	Descent	54	41	4	2	-	12	24	64	36	56	8	-	-	14	50	36	32	48	14	4	62	31	-	-	-	15	38	45	-	-	-	100
	Approach	55	40	3	3	-	4	28	68	44	48	4	-	-	14	36	50	44	32	8	8	38	46	-	8	-	18	30	50	-	-	50	50
	Landing	50	30	9	5	4	-	16	80	48	32	12	8	7	21	21	50	44	32	8	8	38	38	8	8	-	22	12	65	50	-	-	50
	Go Around	41	36	14	9	-	4	12	84	44	42	20	4	-	14	36	57	36	40	12	10	62	8	15	8	-	8	12	78	-	-	-	100
In-and-out	Climb	49	45	5	2	-	20	28	52	40	40	20	-	-	21	43	36	26	46	20	4	46	46	-	8	-	20	40	38	-	-	-	100
	Cruise	41	38	17	3	-	16	16	40	52	36	12	-	7	21	43	29	28	48	18	2	46	46	-	8	-	28	48	22	-	-	-	100
	Descent	51	41	5	3	-	20	24	56	36	44	16	4	-	14	50	36	26	54	12	4	54	38	-	8	-	18	42	38	-	-	-	100
	Approach	50	45	2	2	-	8	28	32	52	36	8	4	-	21	29	50	34	58	6	-	38	46	-	8	-	18	35	45	-	-	50	50
	Landing	53	33	7	6	-	4	16	80	52	32	4	12	7	29	14	50	42	30	18	6	38	38	15	8	-	25	18	55	50	-	-	50
	Go Around	37	42	11	10	-	4	16	80	48	28	20	4	-	14	21	64	38	38	16	8	54	23	15	8	-	5	18	72	-	-	-	100
Clear	Climb	41	41	16	3	-	32	20	48	40	20	32	8	7	29	14	50	38	20	32	4	62	38	-	-	2	22	32	40	-	-	-	100
	Cruise	36	30	28	6	4	24	36	36	48	32	20	-	29	7	29	36	34	34	24	4	69	31	-	-	5	40	30	22	-	-	-	100
	Descent	40	40	17	3	-	32	16	52	40	32	20	8	7	29	14	50	36	30	24	6	69	31	-	-	-	22	38	38	-	-	-	100
	Final	44	38	17	5	-	8	32	60	56	20	16	4	-	21	43	36	38	38	20	-	54	31	15	-	2	35	28	32	50	50	-	-
	Landing	44	35	15	5	-	8	24	68	44	24	20	12	7	21	14	57	38	20	26	12	38	54	-	8	2	32	5	58	50	50	-	-
	Go Around	28	38	20	13	-	8	20	72	32	28	28	12	-	14	29	57	32	18	24	22	46	31	23	-	-	15	15	68	-	-	-	100
Number of responses		111				25				25				14				50				13				40				2			

Note (a) Key for use of HUD: PR = Used as primary flight reference; U = Used, but not primary;
OC = Occasional check; NU = Not used.

TABLE 3

PERCENT USE OF HUDS

UNDER VARIOUS FLIGHT CONDITIONS

AIRCRAFT & HUD	A-7				A-10				AV-8				F-14			
FLIGHT CONDITIONS(a)	SI	I&O	C-D	C-N	SI	I&O	C-D	C-N	SI	I&O	C-D	C-N	SI	I&O	C-D	C-N
No problems	51	67	62	56	20	28	32	4	32	44	68	36	21	14	21	29
Disorientation	12	7	-	4	-	4	-	-	-	4	-	-	7	7	-	-
HUD reliability	5	7	-	5	5	-	-	-	4	-	-	-	-	-	-	-
Lack of required data in display	8	1	1	1	12	4	8	4	40	8	4	8	14	14	14	14
Display symbology	8	5	4	2	4	8	8	12	12	4	4	4	29	21	7	14
Display dynamics	14	3	4	3	-	-	-	-	8	4	4	4	50	57	36	29
Optical properties	1	2	3	1	15	12	40	48	12	4	4	8	-	-	7	7
Brightness	-	5	7	22	-	4	12	48	-	12	8	28	-	-	-	14
Procedures and training problems	4(b)	2(b)	3(b)	3(b)	-	-	-	-	4	-	-	8	14	14	7	-
Do not use HUD	3	2	1	-	60	44	32	24	-	-	4	4	43	43	21	29
No experience in stated conditions	-	-	-	1	-	-	-	4	-	-	-	-	-	-	-	-
Number of responses	111				25				25				14			

AIRCRAFT & HUD	F-15				F-16				F-111				VAH			
FLIGHT CONDITIONS(a)	SI	I&O	C-D	C-N	SI	I&O	C-D	C-N	SI	I&O	C-D	C-N	SI	I&O	C-D	C-N
No problems	30	40	62	50	-	31	69	31	22	28	38	2	-	-	100	100
Disorientation	8	12	-	4	23	-	-	8	5	5	-	-	-	-	-	-
HUD reliability	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Lack of required data in display	28	6	4	8	-	-	-	-	12	8	2	2	-	-	-	-
Display symbology	12	12	6	10	38	15	8	15	12	5	2	2	-	-	-	-
Display dynamics	4	-	4	6	100	62	23	38	62	28	8	12	-	50	-	-
Optical properties	20	26	12	14	38	38	38	38	2	2	2	28	-	-	-	-
Brightness	2	8	20	16	-	8	8	8	-	2	8	42	-	-	-	-
Procedures and training problems	14	2	-	-	23	15	-	-	2	-	-	-	-	-	-	-
Do not use HUD	4	-	2	2	-	-	-	-	25	15	18	10	100	100	-	-
No experience in stated conditions	-	-	-	-	15	-	-	23	-	-	-	-	-	-	-	-
Number of responses	50				13				40				2			

Note (a) Key: SI - Solid instruments; I&O = In-and-out of clouds; C-D = Clear weather - days; C-N = Clear weather - nights.
Note (b) All A-7 procedures and training problems were from A-7D (Air Force) pilots

TABLE 4

PERCENT OF PILOTS REPORTING DIFFICULTIES

WHEN USING HUDS

	FORMAT PROBLEM	A-7	A-10	AV-8	F-14	F-15	F-16	F-111	VAM
		AIRCRAFT AND HUD							
	None	48	28	12	36	46	15	2	100
Symbology	Clutter	23	-	4	14	2	8	10	-
	Backwards scales	8	4	-	-	24	8	-	-
	Moving scales	2	-	-	-	-	77	-	-
	Difficult to interpret	3	8	-	28	4	-	12	-
	Lines too coarse	1	-	12	-	-	-	-	-
	No rate information	-	-	12	14	-	-	-	-
	Differs from head-down	1	-	8	28	-	-	-	-
	All lines identical	-	-	-	7	-	-	-	-
	Move discretes to top	-	-	-	7	-	-	-	-
Data	Need bank reference	1	-	4	-	-	-	-	-
	Need velocity vector	-	4	-	-	-	-	-	-
Compatibility	Effect of strong winds	10	-	-	43	2	-	-	-
	Comparison with real world	-	-	8	-	-	-	2	-
	Distracting	1	-	-	14	2	-	-	-
	Disorienting	-	-	-	-	-	-	2	-
	Blocks real world	-	8	-	-	-	-	-	-
	Inaccurate	-	-	4	-	-	-	-	-
Sensitivity	Too sensitive	-	-	-	28	10	-	38	-
	Jitter	1	-	-	43	-	-	-	-
	ILS sensitivity	-	-	-	-	2	23	-	-
	HUD goes "speghetti"	-	-	4	-	-	-	-	-
	Velocity vector unusable	-	-	-	7	-	-	-	-
Optical	Inadequate field-of-view	3	8	24	43	10	31	5	-
	Bad eye reference point	2	-	16	-	10	23	5	-
	Focus problems	-	-	-	-	-	-	15	-
	Distortions	1	-	-	-	-	-	12	-
	Dark areas in combiner	-	20	-	-	-	-	-	-
	Multiple images	-	16	-	-	-	-	-	-
	Distorts depth perception	-	-	-	-	-	-	2	-
Intensity	Too bright at night	3	4	4	50	-	-	22	-
	Glare at night	-	-	-	-	-	-	12	-
	Clarity at low intensity	-	-	-	-	-	-	2	-
	Too dim during day	-	-	-	-	-	-	2	-
	Intensity varies with g	-	4	-	-	-	-	-	-
Other	Flashing symbol fails to attract attention	-	-	-	2	-	-	-	-
	Weapons symbology	1	-	-	-	-	-	-	-
	Number of responses received	111	25	25	14	50	13	40	2

TABLE 5

PERCENT OF PILOTS REPORTING FORMAT PROBLEMS

USE OF HUD IN SOLID IMC AND REPORTED TENDANCY TO VERTIGO			AIRCRAFT AND HUD							
			A-7	A-10	AV-8	F-14	F-15	F-16	F-111	VAM
Table IV	Pilots using HUD during IFR conditions. (a)	PR	49.0	-	44.0	-	37.5	54.0	-	-
		U	41.2	10.0	44.0	15.8	40.0	36.5	20.8	-
	Weighted use (b)		69.6	5.0	66.0	7.9	57.5	72.2	10.4	0.0
Reponses	Have you noticed any tendency towards vertigo or disorientation?	Yes	23	4	48	7	34	69	20	-
		No	77	80	52	71	64	31	65	100
Table III	Pilots reporting vertigo elsewhere		23	4	4	14	24	31	10	-
Number of responses received			111	25	25	14	50	13	40	2

Note (a) The average of the responses for the use of the HUD in solid instrument conditions from Table IV. Key: PR = Used as primary flight reference; U = Used, but not primary.

Note (b) The weighted use calculated by USE = PR + $\frac{1}{2}$U

TABLE 6

PERCENT OF PILOTS REPORTING VERTIGO

AND DISORIENTATION

OPTICAL AND BRIGHTNESS PROBLEMS REPORTED			AIRCRAFT AND HUD							
			A-7	A-10	AV-8	F-14	F-15	F-16	F-111	VAM
Questionnaire	Has the HUD produced any eye discomfort?	Yes	5	16	4	-	8	-	32	-
		No	95	80	96	93	82	100	58	100
	Is the brightness control adequate for all conditions?	Yes	61	32	48	71	58	85	25	50
		No	38	68	52	29	40	8	72	50
	Why not?	Too bright (night)	28	40	12	-	10	8	55	-
		Too dim (day)	4	4	12	29	26	-	8	50
		Control	3	4	4	-	4	-	-	-
		Other	1	-	-	7	-	-	-	-
	Can you control the brightness over the entire display? (a)	Yes	81	52	72	86	82	85	50	100
		No	17	40	28	-	12	8	45	-
From Table VI	Inadequate field of view		3	8	24	43	10	31	5	-
	Bad eye reference point		2	-	16	-	10	23	5	-
	Focus problems		-	-	-	-	-	-	15	-
	Distortions		1	-	-	-	-	-	12	-
	Dark areas in combiner		-	20	-	-	-	-	-	-
	Multiple images		-	16	-	-	-	-	-	-
	Distorts depth perception		-	-	-	-	-	-	2	-
	Too bright at night		3	4	4	50	-	-	22	-
	Glare at night		-	-	-	-	-	-	12	-
	Clarity at low intensity		-	-	-	-	-	-	2	-
	Too dim during day		-	-	-	-	-	-	2	-
	Intensity varies with g		-	4	-	-	-	-	-	-
Number of responses received			111	25	25	14	50	13	40	2

Note (a) This question appears to have been misinterpreted by the majority of the respondents.

TABLE 7

PERCENT OF PILOTS REPORTING OPTICAL

AND BRIGHTNESS PROBLEMS

VELOCITY VECTOR USE DURING LANDING			AIRCRAFT AND HUD							
			A-7	A-10	AV-8	F-14	F-15	F-16	F-111	VAM
Table IV	Pilots using HUD for VFR final approach (a)	PR	44	-	56	-	38	54	2	50
		U	38	8	20	21	38	31	35	50
	Weighted use (b)		63	4	66	11	57	69	20	75
Responses	Does the velocity vector line up with the runway?	Yes	50	(c)	(c)	29	46	69	60	(c)
		No	48	(c)	(c)	57	52	31	25	(c)
	Is this a problem?	Yes	9	(c)	(c)	14	12	31	28	(c)
		No	86	(c)	(c)	50	72	62	72	(c)
Number of responses received			111	25	25	14	50	13	40	2

Note (a) The response for the use of the HUD during a clear weather final approach from Table IV. Key: PR = Used as primary flight reference; U = Used, but not primary.

Note (b) The weighter use calculated by USE = PR + ½U

Note (c) These HUDs do not have a velocity vector.

TABLE 8

PERCENT OF PILOTS RESPONDING TO VELOCITY

VECTOR ALIGNMENT QUESTIONS

CLUTTER			AIRCRAFT AND HUD							
			A-7	A-10	AV-8	F-14	F-15	F-16	F-111	VAM
Questionnaire	Is the HUD too cluttered?	Yes	23	4	-	50	22	46	38	-
		With Scales	22	-	-	14	4	8	-	-
		No	36	76	100	29	52	15	58	-
Table III	Pilots reporting clutter (Table III)		6	-	-	29	14	38	2	-
Table VI	Pilots reporting clutter (Table VI)		23	-	4	14	2	8	10	-
Number of responses received			111	25	25	14	50	13	40	2

TABLE 9

PERCENT OF PILOTS REPORTING CLUTTER

ISSUE	COMPARISON OF HUD WITH PANEL INSTRUMENTS	AIRCRAFT AND HUD							
		A-7D/E	A-10	AV-8	F-14	F-15	F-16	F-111	VAM
RELIABILITY	Better than panel instruments	4	-	-	-	18	-	-	-
	Same as panel instruments	61	40	72	43	46	54	22	50
	Worse than panel instruments	35	52	28	57	30	38	62	-
ACCURACY	Better than panel instruments	45	-	40	7	44	46	-	-
	Same as panel instruments	39	32	52	43	48	46	28	-
	Worse than panel instruments	15	52	8	50	4	-	58	50
	Number of responses received	111	25	25	14	50	13	40	2

TABLE 10

PERCENT PILOT ASSESSMENT OF HUD

RELIABILITY AND ACCURACY

	DATA DESIRED IN A HUD	AIRCRAFT AND HUD							
		A-7	A-10	AV-8	F-14	F-15	F-16	F-111	VAM
Data items listed in questionnaire	Airspeed	63	92	100	29	96	100	85	100
	Angle-of-attack	96	52	100	50	78	85	65	-
	Barometric altitude	68	84	100	29	92	100	80	100
	Radar altitude	62	56	100	56	33	54	58	-
	Pitch attitude	83	84	100	93	98	100	80	100
	Velocity vector	97	80	24	43	96	100	60	-
	Vertical velocity	43	40	100	79	34	46	40	100
	Sideslip angle	11	-	100	-	6	7	5	-
	Roll angle	60	68	100	64	84	85	78	50
	Localizer deviation	73	72	8	57	88	100	78	100
	Glideslope deviation	77	76	12	86	88	100	80	100
	TACAN/VOR deviation	37	36	44	50	78	46	43	100
	DME	26	28	44	21	90	77	25	100
	Lateral flight director	57	36	8	7	66	46	72	100
	Vertical flight director	43	28	8	7	60	38	70	100
	Thrust (or equivalent)	12	4	12	-	4	7	-	-
	Instrument comparator	4	8	8	-	6	23	5	50
	Master warning	85	88	12	50	20	92	72	100
Write-ins	Heading	10	12	4	7	2	15	5	-
	Navigational data	10	-	36	-	-	23	8	-
	Fire warning	10	-	-	-	-	-	5	-
	Other	3	-	4	7	10	7	-	-
Comments	Selectable declutter	18	20	36	14	18	-	10	50
	Digital scales	22	-	4	-	-	-	8	-
	Deviation scales	4	-	-	-	2	-	2	-
	Better field-of-view	4	4	12	-	6	31	8	-
	Better eye reference point	1	-	-	-	6	15	-	-
Number of responses received		111	25	25	14	50	13	40	2

TABLE 11

PERCENT OF PILOTS DESIRING SPECIFIC DATA

IN A HUD USED IN IMC

TYPE OF DATA	DATA ITEM TO BE ADDED	AIRCRAFT AND HUD							
		A-7	A-10	AV-8	F-14	F-15	F-16	F-111	VAM
Nil	Nothing	20	12	-	21	16	8	2	-
Flight Parameters	Bank reference	10	4	8	-	6	-	2	50[a]
	Velocity vector	-	40	8	-		-	-	-
	Angle-of-attack	3	-	-	-	6[b]	-	18	-
	Load factor (g's)	5	4	-	-	4	-	-	-
	Thrust or fuel flow	6	-	4	-	-	-	-	-
	Force vector	-	-	4	-	-	-	-	-
	Airspeed: IAS	-	-	4	7	-	-	2	-
	Mach	-	-	4	-	2	-	-	-
	CAS	-	-	4	-	-	-	-	-
	TAS	1	-	-	-		-	-	-
	Vertical velocity	-	-	-	-	12[b]	-	-	-
	Altitude	-	4	-	-	-	-	-	-
	Pitch symbol	-	4	-	-	-	-	-	-
	Finer pitch lines	2	-	-	-	-	-	-	-
	Sideslip angle	1	-	-	-	-	-	-	-
	Energy management scale	-	-	-	-	2	-	-	-
Navigational Data	DME	6	-	-	-	24	-	2	-
	ILS: Course reference	-	-	-	-	-	23	-	-
	Raw data	-	-	-	-	2	8	-	-
	Radio altitude	-	4	-	-	6	-	-	-
	Pull-up cue	6	-	-	-	-	-	-	-
	Flare cue	-	-	-	-	-	-	-	50
	VOR/TACAN deviation	8	-	12	-	-	-	-	-
	Heading	-	20	-	-	-	-	8	-
	Clock	4	-	-	-	2	-	-	-
	Radio frequency	2	-	20	-	-	-	-	-
	Groundspeed	1	-	-	-	-	-	8	-
	Navigational data	-	-	4	-	2	-	-	-
Warn	Gear down indicator	-	-	-	-	2	-	-	-
W/D	Weapons items	4	8	-	29	10	8	10	-
Number of responses received		111	25	25	14	50	13	40	2

Note (a) This HUD is not roll-stabilized. This reply may mean that roll-stabilization is desired.

Note (b) These data are desired regardless of gear position.

TABLE 12

PERCENT OF PILOTS INDICATING FIRST PREFERENCE

OF DATA TO BE ADDED TO HUD

TYPE OF DATA	DATA ITEM TO BE DELETED	AIRCRAFT AND HUD							
		A-7	A-10	AV-8	F-14	F-15	F-16	F-111	VAM
Nil	Nothing	-	32	8	-	12	-	10	(a)
Flight Parameters	Airspeed	37	12	32	7	4	-	2	-
	Vertical velocity	30	-	-	-	-	8	-	-
	Altitude	23	-	8	7	6	-	18	-
	"Scales"	8	-	-	-	-	-	-	-
	Pitch symbol	-	4	-	12	-	-	-	-
	Pitch ladder	-	-	-	-	2	15	-	-
	Angle-of-attack	-	-	8	29	6	-	-	-
	Velocity vector	-	-	-	21	-	-	8	-
	Mach number	-	-	-	-	10	-	-	-
	Load factor (g's)	1	-	-	-	4	-	-	-
	Sideslip angle	-	-	4	-	-	-	-	-
	Roll angle	-	4	-	-	-	-	-	-
Navigation	UHF homer	-	-	32	-	-	-	-	-
	TACAN deviation	-	-	16	-	-	-	-	-
	Heading	1	-	4	7	2	-	-	-
	ILS Glideslope descretes	-	-	-	-	8	-	-	-
	ILS display	1	-	-	-	-	-	2	-
	Flight director	2	-	-	-	2	-	-	-
	Inertial data	-	-	-	-	4	-	-	-
Descretes	Data box right	-	-	-	-	-	23	-	-
	Data box left	-	-	-	-	-	15	-	-
	Fuel descrete	-	-	-	-	-	-	10	-
	Warning	-	-	-	-	-	-	2	-
W/D	Weapons item	-	24	-	-	6	-	12	-
Entire Display	E/M display	-	-	-	-	-	23	-	-
	Landing display	-	-	-	21	-	-	-	-
	All but TAS	-	4	-	-	-	-	-	-
	Entire HUD	-	-	-	-	-	-	2	-
Number of responses received		111	25	25	14	50	13	40	2

Note (a) Because of the limited data shown on the VAM, this question was not asked of these pilots.

TABLE 13

PERCENT OF PILOTS INDICATING FIRST PREFERENCE

OF DATA TO BE REMOVED FROM HUD

TRAINING AND PROCEDURAL QUESTIONS AND ISSUES			AIRCRAFT AND HUD								
			A-7D	A-7E	A-10	AV-8	F-14	F-15	F-16	F-111	VAM
Questionnaire Responses	Was your initial HUD training adequate?	Yes	95	74	84	92	14	92	46	72	50
		No	5	21	8	4	86	4	54	18	50
	Are the published HUD procedures adequate and appropriate for IMC?	Yes	82	58	52	40	28	64	8	48	50
		No	14	16	4	4	7	16	31	20	50
	Would a HUD help in primary pilot training or in checkout in a new airplane?(a)	Yes	53	42	48	52	71	48	54	32	100
		QY	4	5	4	4	-	8	-	-	-
		C/O	3	16	-	-	-	8	-	-	-
		No	16	21	24	44	14	20	23	48	-
		QN	15	11	4	-	-	12	-	-	-
Table XVI	Pilots with other HUD experience		3	10	52	8	7	10	62	2	-
	Did previous HUD experience help or hinder adapting to a new HUD?	Helped	1	5	32	4	-	8	38	-	-
		Neither	1	-	16	4	7	2	16	-	-
		Hindered	-	1	4	-	-	-	8	2	-
		Both	-	-	-	-	-	-	8	-	-
Number of reponses received			92	19	25	25	14	50	13	40	2

Note (a) Several pilots qualified their answers by cautioning against over dependence on the HUD by the student. These are shown as a qualified yes (QY) or a qualified no (QN). A few pilots said the HUD would be helpful in checkout, but not in primary pilot training. These replies are shown by C/O

TABLE 14

PERCENT OF PILOTS RESPONDING TO TRAINING AND

PROCEDURAL ISSUES QUESTIONS

CURRENT AIRCRAFT	PILOT EXPERIENCE		OTHER HUD FLOWN	WHICH HUD PREFERRED	WHY?	DID HAVING HUD EXPERIENCE HELP OR HINDER ADAPTATION
	TOTAL	IN TYPE				
A-7	625	200	F-16(sim)	A-7	Only one I really know	--
	1250	250	F-111	A-7	Velocity vector	Helped
	1350	950	F-18(sim)	F-18	Digital scales, sel. declutter	Helped
	2200	1400	Jaguar	Either	Essentially the same	Neither
A-10	380	125	T-38	Neither		Helped
	650	105	A-7	A-7	Velocity vector, heading	Hindered
	740	140	A-7	A-7	Velocity vector	Neither
	900	195	A-7	A-7	Accuracy	Neither
	900	220	A-7	A-7		Helped
	1700	500	A-7	A-7	Velocity vector	Neither
	2000	450	A-7	A-7	Velocity vector and pitch	Helped
	2263	253	A-7	A-7	Velocity vector	Helped
	2600	320	A-7	A-7	It's a real HUD	Neither
	3100	330	A-7	A-7	More complete	Helped
	3500	150	A-7	A-7	More information	Helped
	3800	150	A-7	A-7	More functional	Helped
	4100	250	A-7	Combination	Format: A-10; AOA/FPM: A-7	Helped
AV-8	1390	600	A-4	AV-8	Digital scales	Helped
	3200	200	A-4	AV-8	More information	Neither
F-14	2100	200	RA-5C	F-14		Neither
F-15	1400	210	A-7	F-15	Altitude scale w/ gear down	Helped
	1500	300	A-7	F-15	Better scales	Neither
	1600	300	A-7	A-7	Displays ground waypoints	Helped
	2100	500	A-7	A-7	Declutter	Helped
	2600	175	A-7	Either		Helped
F-16	1500	20	A-7	A-7	ILS and design eye point	Helped
	1600	100	A-7	Either		Helped
	2400	100	Jaguar	Jaguar	Better organization	Neither
	3000	11	A-7,F-4	A-7	More stable	Helped
	3000	700	A-7,F-4,F-15	F-16	Best overall setup	Both
	3300	160	A-7	Either		Helped
	3500	120	A-7	A-7	Flight director	Neither
	3722	220	A-7	Either	Basically the same	Helped
F-111	2500	1000	F-4	Neither	Poor pitch reference	Neither

TABLE 15

RESPONSES BY PILOTS

WITH EXPERIENCE FLYING

MORE THAN ONE HUD

A-7D Comments	
5 comments	De-emphasize HUD; conduct HUD-out training
3 comments	Need how-to-use-HUD-data training; Need how-to-use-velocity-vector training.
1 comment	Stress use of scales
1 comment	Need better classroom description with mockup; "It's easy to understand HUD if you know what it's telling you."
1 comment	"I had practice with a symbol generator and two simulator rides."
1 comment	(an ex-T37 IP) HUD "would be great for teaching 'the picture' for several phases of training, then turned off as the student gets the feel of level flight, level turns, landing glideslopes, etc."
A-7E Comments	
3 comments	Insist on HUD as a primary flight reference.
2 comments	Need how-to-use-HUD-data training.
1 comment	"Old timers don;t trust HUD and they should. It usually takes a dark rainy night at the ship to convince them."
1 comment	Need training to teach where HUD data originates and how it is processed.
1 comment	"can be relied upon too heavily such that HUD failure becomes more debilitating than is necessary."
A-10 Comment	
1 comment	No training received.
AV-8 Comments	
1 comment	Need a visual simulator
1 comment	Need more HUD-only training
1 comment	Need more HUD use in weather
1 comment	Had previous HUD training
F-14 Comments	
3 comments	Need more extensive training; Need more HUD emphasis; Include HUD earlier in training.
1 comment	Use taped displays; show how to scan.
1 comment	HUD discredited by others.
1 comment	"Because of previous habit patterns, just starting to use HUD," (15 hours in type)
F-15 Comment	
4 comments	Need more use of simulators.
3 comments	Need to train crosscheck including HUD.
1 comment	Need how-to-use-velocity-vector.
1 comment	Need HUD-only sorties to gain confidence.
1 comment	Make sure student understands HUD.
1 comment	"Pilots have a hard time using and teaching its use."
1 comment	Start out with minimum symbols and work up. "Too much too fast confuses people."
1 comment	"Only problem at first was getting used to the HUD. Vertigo during initial checkout."
F-16 Comments	
2 comments	Need more simulator training.
1 comment	"What training?"
VAM Comments	
1 comment	"Didn't have any! Wouldn't permit a pilot to use the system until trained." (B-737 IP)

TABLE 16

COMMENTS ON TRAINING

A-7D Comments	
3 comments	AFM-51-37 has nothing.
A-7E Comments	
2 comments	Need better manuals.
2 comments	Correct some diagrams; update as equipment is changed.
A-10 Comment	
1 comment	Need techniques for HUD use.
F-15 Comments	
2 comments	Need HUD procedures.
2 comments	Need crosscheck procedures
2 comments	Need better description of various modes of operation, including sub-normal modes.
2 comments	Unusual attitude recovery difficult with HUD.
1 comment	Too vague
1 comment	Can't use AFM-51-37 bank angles without bank reference.
1 comment	Have no chance for weather experience.
F-16 Comments	
2 comments	Need HUD procedures/techniques.
2 comments	Need ILS technques with HUD; need how-to-use-velocity vector during ILS approaches.
1 comment	Dash-one needs better explanations.
F-111 Comments	
2 comments	Need more specific information.
VAM Comment	
1 comment	"Could be more operationally oriented and better written and illustrated.

TABLE 17

COMMENTS ON PROCEDURES

AND MANUALS

A-7 Comments	
4 comments	Excellent HUD; "A must for future aircraft;" "A-7E HUD is 4.0."
3 comments	Need option to keep heading and delete other scales.
2 comments	HUD altimeter should read same as panel altimeter.
2 comments	Expand field-of-view.
2 comments	Need better ILS; present ILS very confusing.
1 comment	"As used longer, like it very much. Depend on AOA," (A-7D pilot)
1 comment	Reduce clutter
1 comment	Expand brightness control (Both day and night).
1 comment	Would prefer digital AOA vice bracket.
1 comment	Use F-16 HUD.
1 comment	Improve avionics reliability.
1 comment	HUD should not be primary.
1 comment	"Do not use or recommend HUD for instruments. HUD doesn't have enough. Poor crosscheck."
F-15 Comments	
3 comments	F-15 HUD is good. "F-15 HUD is S--- hot!"
1 comment	I use head-down to establish flight conditions, then switch to HUD."
1 comment	"HUD will never be primary flight reference -- too much is needed and clutter will result.
1 comment	Flight director should be oriented to waterline.
1 comment	Respondent drew two pictures of HUD symbology.
1 comment	Prefers to fly HUD, but doesn't trust its lack of redundancy; hence tends to fly head-down in weather.
1 comment	Have combiner glass tilt as seat is moved.
1 comment	Expand field-of-view.
1 comment	Use A-7 type angle-of-attack.
1 comment	Invert airspeed.
1 comment	TD box does not flash fast enough to attract attention.
2 comments	Additional issues not raised in questionnaire.
F-16 Comments	
4 comments	Expand field-of-view; "You can never get enough field-of-view."
2 comments	Design eye point too low; "Somebody should talk to a pilot or two before establishing the design eye. The F-16's is poor."
1 comment	ILS problems
1 comment	"The aircraft handling qualities and HUD configuration make precise instrument flying very difficult. One must develop techniques peculiar to the F-16 to compensate for undesirable approach characteristics."

TABLE 18

GENERAL COMMENTS

A REVIEW OF HUD TRAINING

Since training appears to be a significant issue in the operational use of HUDs, the task of reviewing the progress of an A-7D unit during its initial stages of flying HUD-equipped airplanes was undertaken. During this task, several pilots were followed through their first year of flying an airplane equipped with a HUD.

In addition, sufficient questionnaires were received during the course of the HUD survey to permit an examination by experienced and inexperienced A-7 pilots in an attempt to see if there are any differences between the two groups. During the course of talking with several pilots flying HUD-equipped airplanes, it became clear that there was no emphasis being placed on HUD training during the initial checkout or during recurrent training. Because of this observation, a cursory review of existing HUD training was also performed.

MONITORING OF PILOTS DURING INITIAL HUD FLYING

In the summer of 1978, the 178th TFG, Ohio ANG, converted from the F-100D/F, Super Sabre, to the A-7D, Corsair II. Only two of the unit's pilots had previous A-7D experience. Because of the author's close proximity to the unit and the interest in HUD training, the progress of several of the pilots was followed during the first year of flying the A-7D.

Several of the unit's pilots completed the questionnaire survey discussed previously and cited as Reference (41). These questionnaires

have been included in the results of the survey. Ten pilots from this group were asked to complete additional questionnaires during their first year of A-7D flying. Of these, nine provided useful information. (Note, where a pilot completed more than one questionnaire, only the last one completed was used in the HUD survey of the previous section.)

These nine pilots had previous flying experience ranging from 500 hours to over 4000 hours at the time of A-7D checkout. Seven pilots completed two questionnaires and two completed three. Table XIX shows the level of experience of these pilots, the A-7D flying time at the time of completing each questionnaire, and the reported operational problems listed on the first and last questionnaire. Circumstances permitted a great deal of amplification and clarification on some of the points mentioned in these questionnaires.

Of interest is the amount of use the pilots placed on the HUD. Table XX shows the change in use of the HUD under various weather conditions as the pilots gained more experience with the HUD. Several pilots increased their use of the HUD; several decreased use; and one pilot stopped using the HUD altogether (except for weapons delivery). This table also shows the changes in the replies to the question regarding format problems including symbology, optical problems, etc.

Table XXI documents the changes in the pilots' assessment of HUD accuracy and reliability as they became adapted to the HUD. Table XXII shows the changes in answers to several questions regarding HUD problems and HUD training/procedures. Significantly, several pilots at first thought that their HUD training was adequate, but later changed their minds.

PILOT	FLYING EXPERIENCE(a)				PROBLEMS REPORTED WITH HUD	
	TOTAL	IN TYPE			FIRST QUESTIONNAIRE	SECOND QUESTIONNAIRE
Pilot 1	500	70	-	140	C-D: Reflections C-N: Too bright	SI: Velocity vector disagrees with ADI -- confusing
Pilot 2	550	20	60	120	Scales interfere with real world(b),(c)	No problems
Pilot 3	550	100	-	200	No problems	No problems
Pilot 4	1300	60	-	300	SI: Lack of roll data I&O: Lack of roll data	SI: Disorientation because of lack of roll data
Pilot 5	2500	50	-	200	HUD fixation	HUD fixation
Pilot 6	2500	25	-	100	SI: No problems I&O: Transition to and from HUD C-D HUD fixation	SI: Disorientation I&O: No problems C-D: No problems C-N: No Problems
Pilot 7	2900	30	-	200	SI: Tend to revert to head down I&O: Distraction with real world C-D: HUD fixation	All: Can't read scales; must duck down
Pilot 8	3900	50	110	190	SI: No problems(b),(c) I&O: Intensity variations(c) All: No problems(b)	SI: Don't use I&O: Intensity variations C-D: Reflections
Pilot 9	4200	15	-	250	No problems	C-N: Disorientation during pull-ups

Note (a) Flying experience: Total Time is that shown at the completion of the first questionnaire. The times for experience In Type are those shown at the completion of each questionnaire.
Note (b) First questionnaire
Note (c) Second questionnaire

TABLE 19

PILOTS MONITORED DURING

INITIAL A-7D FLYING AND PROBLEMS REPORTED

PILOT	CHANGE IN USE OF HUD				CHANGE IN FORMAT PROBLEMS REPORTED	
	SI	I&O	Clear	Landing	First Questionnaire	Second Questionnaire
Pilot 1	PR → U	PR → U	PR → PR	PR → PR	Too cluttered	No problems
Pilot 2	PR → PR	PR → PR	U → U	PR → U	Scales hard to use	Scales hard to use
Pilot 3	PR → PR	PR → PR	PR → PR	PR → PR	No problems	Jitter, distortion
Pilot 4	U → U	U → U	U → PR	U → PR	ILS display	ILS display
Pilot 5	U → U	U → U	U → OC	U → PR	Clutter (with scales)	No problems
Pilot 6	PR → U	U → U	U → U	PR → PR	No problems	No problems
Pilot 7	PR → PR	PR → PR	OC → U	U → PR	ILS display	ILS display
Pilot 8	U → NU	U → NU	U → NU	U → NU	Clutter	No problems
Pilot 9	U → PR	PR → PR	PR → U	PR → U	Angle-of-attack	No problems

Note (a) Key: *PR = Primary flight reference; U = Used, but not primary;* OC = Occasional check NU = Not used. These are the "average responses for all phases of flight except cruise and landing. Most pilots report using the HUD somewhat less in cruise. The symbol → indicates the change from the first to the second questionnaire.

TABLE 20

CHANGES IN HUD USE

AND FORMAT PROBLEMS

DURING INITIAL HUD EXPERIENCE

PILOT	CHANGE IN PERCEPTION OF RELIABILITY	CHANGE IN PERCEPTION OF ACCURACY
Pilot 1	HUD less reliable	HUD equally accurate to less accurate
Pilot 2	HUD less reliable	HUD more accurate
Pilot 3	HUD less reliable to equally reliable	HUD equally accurate to less accurate
Pilot 4	HUD less reliable to more reliable	HUD equally accurate to more accurate
Pilot 5	HUD equally reliable	HUD equally accurate
Pilot 6	HUD equally reliable	HUD equally accurate
Pilot 7	HUD equally reliable to less reliable	HUD more accurate
Pilot 8	HUD less reliable	HUD more accurate to less accurate
Pilot 9	HUD equally reliable	HUD more accurate to less accurate

TABLE 21

CHANGES IN ASSESSMENT OF HUD

ACCURACY AND RELIABILITY

PILOT	HAS THE HUD CAUSED ANY DISORIENTATION?	CAN YOU CONTROL THE BRIGHTNESS?	IS THE HUD CLUTTERED?	WAS YOUR INITIAL HUD TRAINING ADEQUATE?	ARE THE HUD PROCEDURES ADEQUATE?	WOULD A HUD BE USEFUL IN UPT?
Pilot 1	No → No	No → No	Yes → W/S[a]	No → No	Yes → Yes	No → Yes
Pilot 2	No → No	Yes → Yes	W/S → Yes	Yes → Yes	(b) → Yes	Yes → Yes
Pilot 3	No → No	Yes → Yes	W/S → Yes	Yes → Yes	Yes → No	Yes → No
Pilot 4	Yes → Yes	Yes → Yes	Yes → No	Yes → Yes	(b) → (b)	Yes → Yes
Pilot 5	No → No	Yes → Yes	W/S → Yes	Yes → Yes	Yes → No	No → No
Pilot 6	No → No	Yes → Yes	Yes → Yes	Yes → No	Yes → Yes	Yes → Yes
Pilot 7	No → Yes	Yes → Yes	Yes → No	Yes → Yes	No → Yes	Yes → Yes
Pilot 8	No → No	Yes → Yes	Yes → Yes	Yes → No	Yes → No	Yes → Yes
Pilot 9	Yes → Yes	Yes → Yes	Yes → Yes	Yes → No	Yes → No	Yes → Yes

(a) W/S means with scales on (b) No response shown

TABLE 22

CHANGES IN RESPONSES TO SELECTED QUESTIONS

Table XXIII summarizes the significant changes in each pilot's HUD use and attitude from the first to the final questionnaire. The significant findings are:

- There is a tendency to use the HUD more for landing as the pilot gains experience.
- There is a tendency to change the amount of use of the HUD during other phases of flight, but no pattern of increasing or decreasing is apparent.
- Pilot assessment of HUD accuracy tends to decrease as the pilot gains experience.
- Problems of clutter and use of scales continue, but are less severe as the pilot gains experience with the HUD.
- Two pilots report difficulties with using the velocity vector for control after considerable experience.
- Several pilots feel that their HUD training and published HUD procedures are inadequate after gaining considerable HUD experience.
- One pilot became so disenchanted with the HUD that he no longer "uses or recommends its use." Interestingly, he still feels that it would be useful for primary pilot training.

These changes in pilot comments as the pilots gain well over one hundred hours of HUD experience point out the basic lack of training oriented to the HUD. That some of these problems do not appear for some time merely points up the complexity of the issues. The comments relating to the pilots not understanding the use of the velocity vector are interesting in light of the earlier paper on HUD training(45).

PILOT AND EXPERIENCE	PROBLEMS AFTER SOME EXPERIENCE COMPARED WITH INITIAL REACTION
Pilot 1: 500 hours	Uses HUD less in weather. Problems with reflections and brightness are less; problems with confusion between velocity vector and pitch are more. Does not feel that initial HUD training is adequate.
Pilot 2: 550 hours	Less problems with scales.
Pilot 3: 550 hours	Reports problems with jitter and distortion. Now feels that procedures are inadequate.
Pilot 4: 1300 hours	Lack of roll data still a problem, now causing vertigo. Clutter less of a problem.
Pilot 5: 2500 hours	HUD fixation remains a problem. Uses HUD less in clear weather; more for landing. Now feels that procedures are inadequate.
Pilot 6: 2500 hours	Problems have changed from transition to and from HUD and HUD fixation to disorientation in solid weather. Uses HUD less in solid weather. Now requires additional techniques for speed control with velocity vector.
Pilot 7: 2900 hours	Had difficulty using HUD at first; now reports problems with ILS and ERP. Uses HUD more in clear weather and for landing. Now feels HUD procedures are adequate.
Pilot 8: 3900 hours	Initially reported problems with clutter and intensity variations. Now does not use the HUD at all for routine flying. Does not feel that procedures are adequate. Does recommend HUD for UPT.
Pilot 9: 4200 hours	Initially reported problems with AOA, but not at present. Problems now reported with disorientation during night pull-ups. Now feels that initial training and HUD procedures are inadequate

TABLE 23

SUMMARY OF CHANGES IN RESPONSES DURING INITIAL HUD FLYING

CURRENT TRAINING TECHNIQUES

A limited review of current syllabi for HUD training revealed a general lack of dedicated training within operational units. The following training methods were reported:

A-7D	Programmed texts covering HUD(47,48).
A-10	Slide/cassette audio visual presentation.
F-15	Written material (Dash one and Dash thirty-four plus handout material), followed by a cockpit procedures trainer (CPT) session (switches work, but no display), followed by a one hour class.
F-16	Two sessions in a CPT. A visual simulator is coming on line shortly.
CH-3E	During the MARS/HUD testing, a one-hour in-flight practice session was scheduled for each subject. The report(43) concluded that this was insufficient.
Air Inter	The pilots are not given HUD training during their initial aircraft checkout. Following several months of line flying, about 200 hours of flying, the pilots receive a one week category 3 (CAT III) course which covers the use of the HUD. The first day is theoretical and covers the HUD, the data presented, and possible sources of errors. Following the first day of class, the pilot receives three days of simulator checkout starting with visual approaches and working down to CAT III weather. Much attention is paid to the effect of wind on the HUD data. Upon completion of the training, the pilot must make ten approaches using CAT III (and HUD) procedures, but with higher minimums. Then, following a line check, the pilot will be fully qualified.
NASA	During recent NASA conducted HUD simulator studies, each subject received a package of material describing the HUD several weeks in advance. He was shown video tapes of the presentation. His "hands-on" training consists of increasing the complexity of the HUD display while allowing him to fly the display on a part-task trainer. The display complexity is increased until the full level of complexity (and lowest weather) is reached.*

* Dr. Richard F. Haines, NASA Ames Research Center, private communication, September 1979 and January 1980.

In the early 1970s, the Air Force Human Resources Laboratory (AFHRL) studied this problem and investigated the feasibility of incorporating an audio/visual recorder to record the HUD and real world cues and the pilot's comments as a teaching aid(49,50). This hardware was installed in an A-7D and a trial training evaluation conducted. For technical reasons, only IPs were allowed to fly the airplane, not student pilots. As a result, it was not used as a student debriefing aid, but only as a classroom teaching aid to demonstrate the HUD symbology in operational situations. The results indicated that this approach can be of real value in the training of HUD pilots.

This approach or the simulator/classroom training of Air Inter would help the situation, described by Pilot 1 in the previous subsection, of "Not knowing what the HUD was going to show me before my first ride."

EFFECT OF PILOT EXPERIENCE ON HUD SURVEY

During the previous HUD survey, sufficient questionnaires were received from A-7 pilots to draw some comparisons between experienced and inexperienced pilots. The significant results are shown in the following tables. Table XXIV shows the reported problems as a function of pilot experience. The criteria used to separate low from high experience was 1000 flying hours total time. The criteria for low versus high time in type was 300 hours in A-7s. Perhaps the only significant differences in this table are the experienced pilots were more likely to report "lack of required data in the display." They were also more likely to report optical or brightness problems. This may be an indication that they are older and would be more likely to report visual problems HUD or no HUD.

TOTAL EXPERIENCE[a]	HIGH LEVEL OF TOTAL EXPERIENCE								LOW LEVEL OF TOTAL EXPERIENCE								HIGH EXPERIENCE			
TIME IN TYPE[b]	HIGH A-7D TIME				LOW A-7D TIME				HIGH A-7D TIME				LOW A-7D TIME				HIGH A-7E TIME			
FLIGHT COND.[c]	SI	I&O	C-D	C-N	SI	I&O	C-D	C-N	SI	I&O	C-D	C-N	SI	I&O	C-D	C-N	SI	I&O	C-D	C-N
No Problems	44	72	74	60	57	52	52	52	70	80	60	60	50	67	50	50	32	37	42	42
Disorientation	16	14	-	2	-	-	-	5	10	-	-	-	6	-	-	-	16	11	-	5
HUD Reliability	12	7	9	9	-	-	-	-	-	-	-	-	6	-	6	6	16	11	-	5
Lack of Required Data in Display	9	-	-	-	10	5	5	5	-	-	-	-	6	-	-	-	5	-	-	-
Display Symbology	2	-	2	2	10	10	5	5	10	10	-	0	11	0	6	-	11	11	-	-
Display Dynamics	21	2	5	5	5	5	-	-	20	10	10	10	17	-	-	-	5	-	5	-
Optical Properties	2	2	2	2	-	5	5	-	-	-	-	-	-	-	-	-	-	-	-	-
Brightness	-	-	2	19	-	14	5	24	-	10	10	20	-	11	6	22	-	11	11	26
Procedures and Training Problems	2	-	-	2	5	5	10	5	10	-	-	-	6	6	6	6	-	-	-	-
Do not use HUD	2	-	-	2	-	5	-	-	-	-	-	-	-	-	-	-	11	5	5	-
No experience in stated conditions	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6	-	-	-	-
Number responding	43				21				10				18				19			

Note (a) The dividing line between high and low total experience was taken as 1000 hours of flying time.
Note (b) The dividing line between high and low time in type was taken as 300 hours of A-7D/E time.
Note (c) Key: SI = Solid instruments; I&O = In-and-out of clouds; C-D = Clear weather - days; and C-N = Clear weather - nights.

TABLE 24

PERCENT HUD PROBLEMS VERSUS PILOT EXPERIENCE

Table XXV lists the use of the HUD by phase of flight and by weather conditions. The chief differences here are the tendency of the highly experienced pilots to use the HUD less during landing (except for the Navy pilots who tended to use the HUD more). The less experienced pilots tended to use the HUD more during landing, but less during flight in VMC.

Table XXVI shows the responses to the accuracy and reliability questions. The experienced pilots (total experience) were more likely to be critical of the HUDs reliability than the less experienced pilots. Both the high/high (high total experience and high time in type) and the low/low pilots groups were more likely to feel that the HUD was more accurate than the panel instruments.

Table XXVII shows the answers to additional HUD issue questions as functions of pilot experience. It is interesting to observe that Air Force A-7D pilots are more inclined to feel that the velocity vector lines up on the runway than do Navy A-7E pilots. This may reflect the moving touchdown point in a carrier landing. On the training/procedures issues, the experienced pilots (the high/high group) were more likely to be critical of the HUD procedures than the other groups. They may have felt that their historical procedures were incompatible with the HUD.

A surprising observation was that the older and more experienced pilots were more in favor of using a HUD in primary pilot training. The less experienced pilots (the low/low group) were the least favorable to this idea.

WEATHER	PHASE OF FLIGHT	HIGH LEVEL OF TOTAL EXPERIENCE								LOW LEVEL OF TOTAL EXPERIENCE								HIGH EXPERIENCE			
		HIGH A-7D TIME				LOW A-7D TIME				HIGH A-7D TIME				LOW A-7D TIME				HIGH A-7E TIME			
		PR[a]	U	OC	NU	PR	U	OC	NU	PR	U	OC	NU	PR	U	OC	NU	PR	U	OC	NU
SOLID INSTRUMENTS	Climb	47	50	3	-	71	14	10	5	80	20	-	-	44	50	6	-	11	79	5	5
	Cruise	47	37	16	-	37	37	21	5	50	40	10	-	39	44	17	-	32	42	21	5
	Descent	59	39	2	-	67	24	5	5	70	30	-	-	56	39	6	-	16	74	5	5
	Approach	49	47	5	-	57	38	-	5	70	30	-	-	61	33	6	-	53	37	-	11
	Landing	42	32	21	5	65	25	-	10	40	50	-	10	61	28	11	-	58	32	-	-
	Go Around	53	21	12	14	48	38	5	10	40	40	20	-	33	50	17	-	11	53	21	11
IN-AND-OUT	Climb	49	51	-	-	62	24	10	5	70	30	-	-	50	44	6	-	21	63	11	5
	Cruise	37	44	25	-	43	33	19	5	60	30	10	-	53	35	12	-	32	37	21	11
	Descent	53	44	2	-	57	33	5	5	80	20	-	-	56	44	-	-	32	47	11	11
	Approach	47	51	2	-	57	43	-	-	80	20	-	-	56	44	-	-	32	53	5	11
	Landing	44	37	12	7	62	29	5	5	40	50	-	10	67	22	11	1	58	32	-	11
	Go Around	40	35	9	16	43	43	5	10	30	50	20	-	39	50	11	-	26	47	16	11
CLEAR	Climb	43	41	16	-	29	48	19	5	50	40	10	-	44	39	11	6	37	37	21	5
	Cruise	33	37	28	2	19	29	38	14	40	50	-	10	50	22	22	6	47	11	37	5
	Descent	40	42	19	-	29	57	10	5	60	30	10	-	41	35	18	6	42	26	26	5
	Final	49	35	16	-	38	52	10	-	50	50	-	-	56	39	6	-	63	37	16	5
	Landing	33	33	25	7	43	48	10	-	40	50	-	10	56	28	18	-	63	26	5	5
	Go Around	24	38	24	14	19	43	14	24	40	40	10	10	41	35	18	6	32	37	26	5
	Number	43				21				10				18				19			

Note (a) Key: PR = Used as primary flight reference; U = Used, but not primary; OC = Occasional Check; and NU = Not used.

TABLE 25

PERCENT USE OF HUD VERSUS PILOT EXPERIENCE

COMPARE HUD TO PANEL INSTRUMENTS	HIGH LEVEL OF TOTAL EXPERIENCE						LOW LEVEL OF TOTAL EXPERIENCE						HIGH EXPERIENCE		
	HIGH A-7D TIME			LOW A-7D TIME			HIGH A-7D TIME			LOW A-7D TIME			HIGH A-7E TIME		
	HB[(a)]	EQ	HW	HB	EQ	HW	HB	EQ	HW	HB	EQ	HW	HB	EQ	HW
Reliability	1	23	19	-	15	6	-	6	4	3	11	4	-	7	6
Accuracy	22	14	7	5	11	5	-	7	2	12	4	2	7	5	1

Note (a) Key: HB = HUD is better than panel instruments; EQ = HUD and panel instruments are equal; and HW = HUD is worse than panel instruments.

TABLE 26

PERCENT ASSESSMENT OF HUD RELIABILITY AND

ACCURACY VERSUS PILOT EXPERIENCE

QUESTIONS	HIGH LEVEL OF TOTAL EXPERIENCE								LOW LEVEL OF TOTAL EXPERIENCE								HIGH EXPERIENCE			
	HIGH A-7D TIME				LOW A-7D TIME				HIGH A-7D TIME				LOW A-7D TIME				HIGH A-7E TIME			
	YES	QY[a]	QN	NO	YES	QY	QN	NO	YES	QY	QN	NO	YES	QY	QN	NO	YES	QY	QN	NO
Does the HUD line up on final?	63			37	38			62	50			40	72			28	16			79
Has the HUD caused vertigo or disorientation?	26			74	14			86	20			80	22			78	21			74
Has the HUD caused eye discomfort?	5			95	5			95	-			100	11			89	-			100
Is the brightness OK?	72			28	52			43	50			50	61			39	53			47
Is the HUD cluttered?	26	26[b]	-	49	48	5[b]	-	29	20	30[b]	-	50	39	17[b]	-	44	47	37[b]	-	16
Was your HUD training OK?	95			5	90			10	90			10	94			6	74			21
Are the procedures OK?	81			16	71			24	90			-	89			6	58			16
Would a HUD help training?	49	5[c]	19[c]	14	71	-	10[c]	14	80	10[c]	-	10	39	11[c]	28[c]	17	53	16[c]	11[c]	26
Number replying	43				21				10				18				19			

Note (a) Key: QY = Qualified yes and QN = Qualified no. Note (b) Qualified by "with scales."
Note (c) Qualified by cautioning against letting the student become overdependent on the HUD.

TABLE 27

PERCENT RESPONSES TO SELECTED QUESTIONS

VERSUS PILOT EXPERIENCE

A REVIEW OF HEAD-UP DISPLAY CHARACTERISTICS

In conjunction with the study of operational problems associated with head-up displays, some understanding of the properties of the various HUDs themselves is needed. This section will review the pertinent properties of most HUDs of interest to this study as well as some proposed HUDs.

GENERAL ARRANGEMENT OF HUDs

HUDs may be classified as to their source of the image, by their optical design, and by other significant response characteristics. Some of these are related, others are not.

Source of the Image

The source of the displayed image in most modern HUDs is a cathode ray tube (CRT) which is driven by a symbol generator computer. The display is simply generated on the fact of the CRT in much the same fashion as a conventional television picture. As an alternative means of generating the image, electromechanical meter movements may be used provided that they are lighted or used to reflect a moving beam of light.

A fundamental difference between the two methods of generating an information display is the response of the display itself. An electromechanical (EM) display will exhibit the response of a typical electrical meter. While this response can be tailored to some extent, it can never be instantaneous. There will always be a meter lag in the display.

The CRT image on the other hand has no inherent lag. Being inertialess, the displayed image can be switched from one extreme of the tube face to the other with no inherent lag. In practice, the apparent response of the image will depend on the rate at which new information is being generated (the frame rate of the driving computer) and the electrical mechanization of the CRT image (stroke written or a television raster).

There are additional implications to the choice of CRT or EM displays. Since the EM display has a moving part, it is possible to monitor the actual display as a check on the displayed (as opposed to the input) accuracy. It is also usually smaller, hence a retrofit HUD may have to be an EM display. The EM display is driven by an analog signal, while the CRT may be driven by either an analog or a digital signal. Usually, the CRT will allow more data to be displayed (because the colocation of several meter movements will cause interference) and will usually be easier to modify the symbology.

There are other means of generating the image, such as a light emitting diode or other image techniques, but these are not yet available.

Optical Design

The typical HUD uses a refractive optical design with a combining glass to superimpose the HUD symbols and the real world. Such a system is shown in Figure 1. In a system of this type, the image of the CRT (or EM) display is conducted optically to produce a parallel set of rays. From elementary optics, a parallel set of rays will appear to be an image focussed at an infinite distance. Usually this set of rays will be projected upwards out of the airplane's instrument panel and will be reflected toward the pilot eye by a semi-transparent mirror. Since this

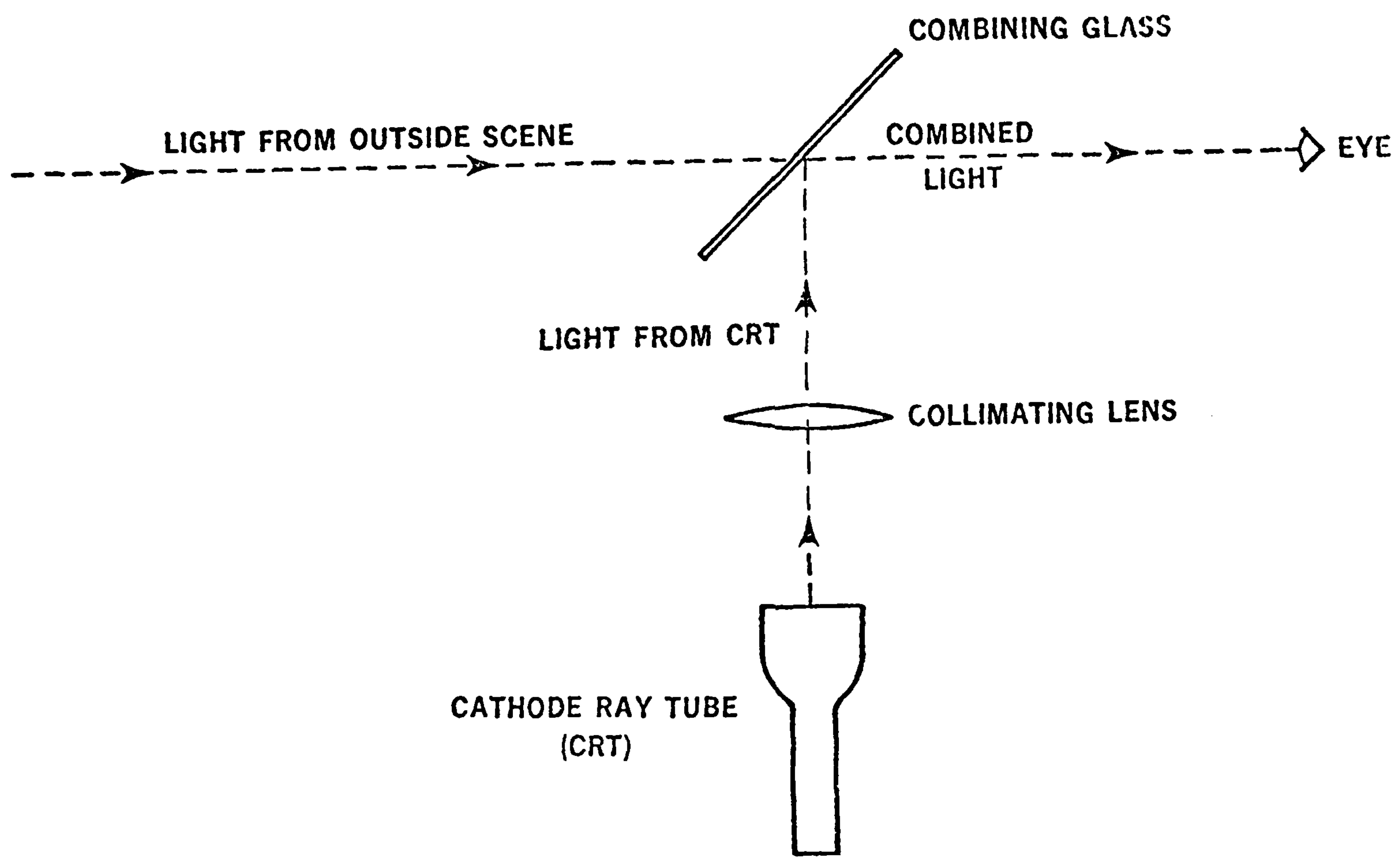


Figure 1

Typical HUD Arrangement

mirror allows the real world cues to pass through, the HUD image and the real world cues are superimposed. This glass is called a combining glass.

The effect created, as is shown in Figure 2, is a virtual image of the HUD symbols appearing to float in space overlying the real world view. Because of the limited capabilities of the optical system, the effect will be a "knothole" approximately the size of the final display lens located about the same distance in front of the combining glass as the lens is located below it. The pilot can only see HUD symbology of this size as he looks through the combining glass. This size is called the instantaneous field-of-view (FOV). Because the pilot's two eyes are not colocated, he will see slightly different FOVs out of each eye. These separate FOVs will be the same size, but will be displaced slightly, forming an oval-shaped instantaneous FOV. Normally, the HUD optics will provide a larger field than this instantaneous FOV, but it will be limited by the knothole effect of the final lens aperture. The total field of view will only be visible to the pilot by moving his head within the exit pupil.

During the 1960s, Gold and co-workers studied the maximum permissible visual disparity between the images received by the pilot's two eyes(12,13,14). The maximum tolerable visual disparity was found to be 1.0 milliradians (mr) for vertical and horizontal divergent disparities and 2.5 mr for convergent horizontal disparities. The location of the design point for the pilot's eye to best view the HUD is called the design eye reference point (ERP). As the pilot moves his head away from this point, additional distortions will be introduced. Gold's figures for allowable binocular disparities state one limit on how much distortion is allowable.

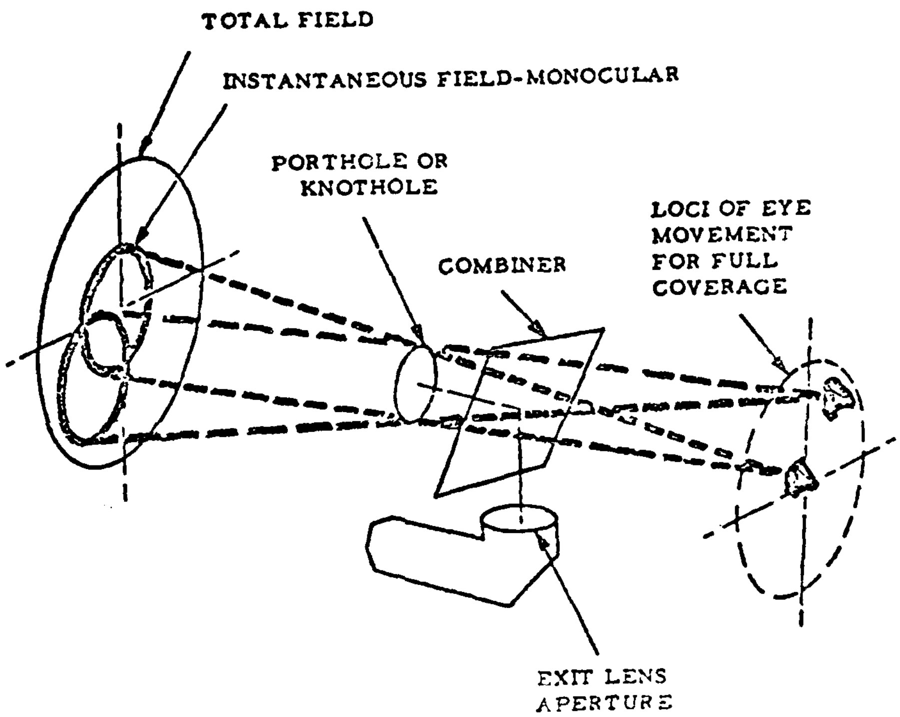


Figure 2

Instantaneous Monocular
Field of View
(from Reference 51)

In addition to the refractive technique for providing a HUD image, some HUDs use a curved combining glass which focusses the image using reflective optics. This type of unit usually provides much greater flexibility in the location of the pilot's eyes and usually allows for an instantaneous FOV to approach the total FOV.

An additional concern of the HUD optics is the displayed accuracy of the cues. For those displays showing conformal cues, where the HUD symbol should overlay the real world, some measure of display accuracy is required to provide for this overlay. Angular accuracies of about 0.1 degree (1.7 mr) have been cited as maximum tolerable values for flight path vector errors(52).

Other approaches are presently being developed for HUD optics. Hughes Aircraft is developing a diffraction optics HUD which is currently being tested on a Viggin fighter(53). The advantages of diffraction optics are cited as a much wider FOV. The proposed HUD for the DC-9-80 will use a solid optical path(54). This HUD will have the light from the symbol generator passing through a piece of plastic with optical surfaces imbedded.

Brightness

A final optical design property required of the HUD is the proper level of image brightness. Because only part of the light that shines on the combining glass is reflected and part transmitted, there will be some loss of brightness from the HUD symbols. If the combining glass is made more reflective, then the pilot may not be able to see the real world cues through it. The image brightness must be of sufficient intensity so the HUD cues are visible even in bright sunlight. At the same time, an

automatic brightness control must adjust the image to allow for variations in the background illumination level.

At night, the brightness control must be sufficiently sensitive so the HUD may be turned down to a level compatible with the dimly lit cues available at night. This will require a great deal of range and precise control of the HUD brightness and possible use of light filters in the HUD.

Stray reflections must also be avoided, from both internal reflections and glare from the HUD at night and stray external reflections from lights or the sun.

Significant Properties of HUDs

The significant properties from the pilot's point of view with a HUD are (optical properties only):

- Field-of-View (FOV)
- Brightness
- Location of Eye Reference Point (ERP)
- Accuracy of the Symbols
- Response of the Symbols
- Freedom from Annoying Reflections, Glare, Distortions, etc.

The types of data to be displayed will be discussed in the following subsection.

HUD CLASSIFICATION

We can classify HUDs into several groups. Since no classification system exists, we propose the following:

- All Purpose HUDs
- [illegible] Approach HUDs

- Limited or Special Purpose HUDs
- Approach or Special Purpose Monitors.

Both the All-Purpose HUD and the ILS Approach HUD provide sufficient cues for the pilot to control the airplane in instrument conditions. They differ in the number of HUD modes available. The All-Purpose HUD has several modes available which allow HUD use in several phases of flight, such as enroute navigation, ILS or visual landing approaches, or various weapons delivery modes. The ILS Approach HUD has only one mode. It could also be called a single-mode HUD, however all instrument HUDs to date have at least included an ILS mode.

The Limited or Special Purpose HUD does not provide sufficient data for safe flight in IMC, although it provides at least a wings-level capability. The Limited HUD would have several modes, while the Special Purpose HUD would usually only be used for a particular phase of flight, such as Mid-Air Recovery System (MARS) recoveries.

An Approach or Special Purpose Monitor is a HUD that does not provide for at least wings level capability. An Approach Monitor is intended to assist the pilot during his landing approach (usually in VMC only) to assure a safe landing trajectory.

All of the HUDs in the questionnaire survey, except the A-10 HUD are classed as All Purpose HUDs. The A-10 does not provide sufficient data to permit safe instrument flight. While some of the others may not be desirable HUDs, they at least meet the intent of this classification.

Table XXVIII lists the various HUDs with their pertinent characteristics. The data for this table were obtained primarily from Augustine's report(55) for military HUDs and from specification or descriptive

CLASS	HEAD-UP DISPLAY		IMAGE TYPE	FIELD-OF-VIEW INST. (deg)	FIELD-OF-VIEW TOTAL (deg)	ACCURACY CENTER (mr)	ACCURACY EDGE (mr)	ILS?	SUR-VEY?	REMARKS	REFER-ENCES
ALL-PURPOSE	Elliott	A-7	CRT	11X17	20X20	2.0	5.0	Yes	Yes		55-58
	Smiths	AV-8	CRT	18X20	25X25	1.5	-	No	Yes		55,59
	Kaiser	F-14	CRT	11X17	20X20	1.0	3.0	Yes	Yes		55,60-62
	McD-D	F-15	CRT	12X17	20X20	-	-	Yes	Yes		55,63-65
	Elliott	F-16	CRT	9X13	20X20	1.7	4.5	Yes	Yes		66,67
	Norden	F-111	CRT	15X16	20X20	0.3	2.5	Yes	Yes		40,55
	SAAB	M3297	CRT	-	15X15	-	-	No	No	Prototype	68
	Sperry	F-4	CRT	15X20	25X25	-	-	Yes	No	Prototype	69
	McD-D	F-18	CRT	-	-	-	-	Yes	No	Being Tested	70
	Sundstr.	DC-9-80	CRT	26X30	-	2.4	2.4	Yes	No	Under development	71,72
ILS LANDING	Thomson	193M	EM	12X18	-	1.0	7.0	Yes	No	in airline use	73,74
	McD-D/Elliott		CRT	-	-	-	-	Yes	No	DC-9 and Falcon	75-78
	Sperry		CRT	11X17	25X25	-	-	Yes	No	CL-84 VTOL test	79
	Thomson	TC-121	CRT	-	20X20	1.1	-	Yes	No	Prototype	80-83
	Bendix	Micro-vision	CRT	20X40	-	-	-	Yes	No	FAA tests	84,85
LIMITED	Kaiser	A-10	CRT	13X13	20X20	1.5	-	No	Yes		86,87
	Sundstr.	MARS/HUD	EM	12X22	12X22	-	-	No	No		43,88
	Sundstr.	Lightline	EM	12X22	12X22	-	-	No	No	T-38 test	85,86
MONITOR	Sundstr.	VAM	EM	12X22	12X22	1.1	-	No	Yes	in airline use	29,87,89
	Thomson	CV-91AB	EM	11X17	-	-	-	No	No		81,95

TABLE 28

HEAD-UP DISPLAYS

literature for those HUDs not included in Augustine's report. These references are cited in the table.

DATA DISPLAYED IN HUDs

A review of operational HUDs will quickly show that there is very little standardization among the various displays. Even with two applicable military specifications(96,97), the military HUDs do not show any great amount of standardization. Table XXIX shows the data items displayed on the various HUDs together with the requirements from the Navy HUD specification(96). It would seem from this table that the HUD designers are not at all sure exactly what is desired in a HUD.

Even the specific symbols do not show any standardization, as can be seen from Table XXX. This lack of standardization has already been documented for military HUDs by Orrick and York(98) and by Green(99). Surprisingly, the proposed DC-9-80 HUD will use the same symbol for both velocity vector and aircraft pitch depending on the mode selection.

How these flight parameters are shown to the pilot cannot be seen from such a table but must be seen in total. Figure 3 shows the HUD specification format(96). Pictures of the various HUDs are shown in Figures 4 through 25. It must be emphasized that these static displays will not show the full impact of any HUD. How the various symbols move - both absolutely and relatively to other symbols - in response to a pilot control input cannot be seen from a static picture or even from a moving picture with no control inputs by the observer.

Unfortunately the HUD specifications do not address the issue of dynamic response, perhaps because it is not solely a HUD problem, but

rather a problem of the entire control/display system in the airplane. At present there is no "systems specification" for electronic displays.

HEAD-UP DISPLAY	A-7D/E		AV-8		F-14			F-15		F-16		F-111		SAAB	SPERRY
Mode	NAV	LDG	NAV	VTOL	TO	CR	LDG	NAV	ILS	NAV	ILS	TO	LAND		
Velocity Vector	X	X					0	X	X	X	X			X	
Aircraft Pitch			X	X	X	X	X	X	X			X	X		X
Pitch Ladder	X	X	X	X	X	X	X	X	X	S	S	X	X		
Roll Index												X	X		
Angle-of-Attack	A	X	S	X			X		A		X				S
Airspeed/Mach	0	0	X					0	0	0(a)	0(a)	X	X	X	S
Altitude	0	0	X	X	X		X	0	0	0	0	X	X	X	X
Vertical Speed	0	0	S	S	0		0	0	0	0	0			X	
Heading	0	0	X	X	0	X	0	0	0	0	0			X	(b)
Sideslip				X											
TACAN/VOR Dev.			S	S	S	S									
DME								(c)	(c)	X	X				
ILS Deviation		X					X				X	X	X		X
Flight Director	X	X					X	X	X	X		X	X	X	
UHF Bearing			S	S											
Time-to-Station								X	X						
Marker Beacon									X						
Load Factor								X	X	X	X				
Warning Discrete	X	X						X	X	X	X				
Pull Up Cue	X					X									
Potential Flight Path Angle															

KEY: X = Displaye
0 = Declutterable
S = Selectable
A = Automatic

(a) Digital Mach number displayed full time
(b) Single heading mark
(c) Early airplanes only; replaced by Time-to-Station
(d) Delta Gamma
(e) Digital pitch information
(f) Synthetic runway from ILS data
(g) Synthetic runway from non-ILS data
(h) Optional; replaces pitch information

TABLE 29

DATA PRESENTED IN HUDs

HEAD-UP DISPLAY	DC-9-80		PERSE POLIS	NASA	193M	McD-D	SPERRY VTOL	TC121	BENDIX	A-10	MARS/ HUD	Light Line	VAM	VC91
Mode	APPR	G/A								FLT				
Velocity Vector	X		X	X	X			X				X	(d)	X
Aircraft Pitch		X	X		X					(e)	X			
Pitch Ladder	X	X			X						X	X	X	X
Roll Index	A	A			X		X				X			
Angle-of-Attack			X		X			X						
Airspeed/Mach	X	X	X	X		X	X		X	X	X	X	X	
Altitude	X	X	X	X		X	X		X	X				
Vertical Speed							X				X			
Heading	X	X	X	X			X	(b)				X		
Sideslip							X				X			
TACAN/VOR Dev.														
DME														
ILS Deviation	X		X	X	X	X	X	(f)	(g)					
Flight Director	X	X				X					(h)			
UHF Bearing														
Time-to-Station														
Marker Beacon			X	X										
Load Factor														
Warning Discrete	X	X			X	X	X							
Pull Up Cue														
Potential Flight Path Angle			X	X				X						

KEY: X = Displayed
O = Declutterable
S = Selectable
A = Automatic

(a) Digital Mach number displayed full time
(b) Single heading mark
(c) Early airplanes only; replaced by Time-to-Station
(d) Delta Gamma
(e) Digital pitch information
(f) Synthetic runway from ILS data
(g) Synthetic runway from non-ILS data
(h) Optional; replaces pitch information

TABLE 29 (continued)

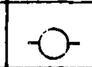
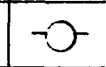
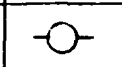
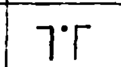
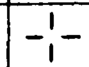
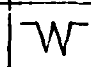
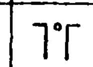
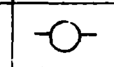
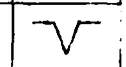
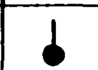
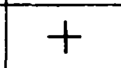
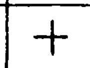
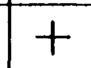
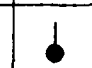
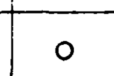
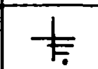
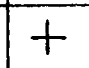
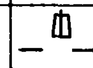
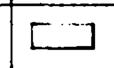
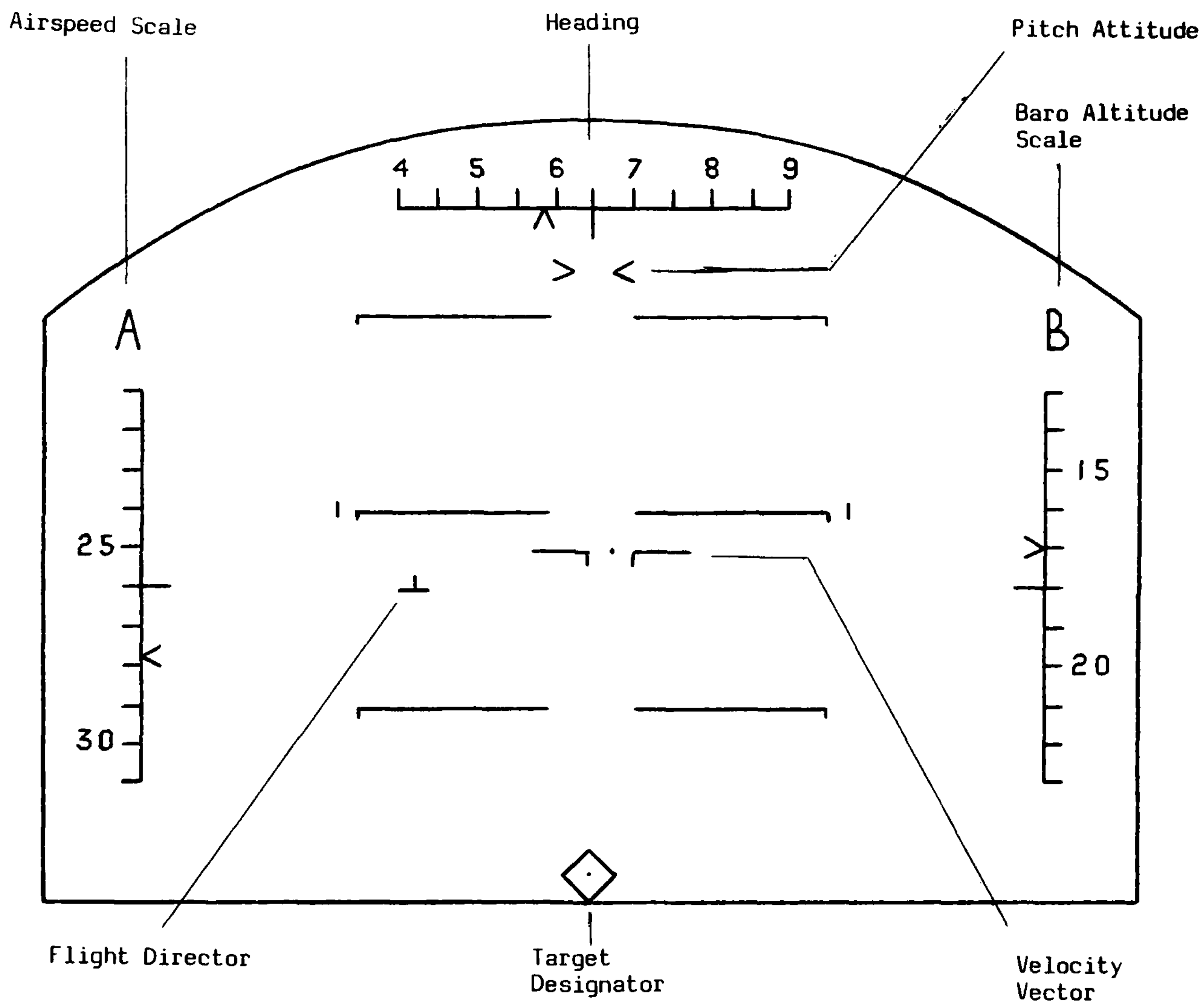
HUD	A-7D/E	AV-8	F-14	F-15	F-16	F-111	SAAB	Sperry	F-18	DC-9-80	NASA
Velocity Vector											
Pitch											
Flight Director											
ILS Deviation											
Pitch Ladder Interval	5 deg	30 deg 5:1 Scale	6 deg or 30 deg 4:1 Scale	5 deg	5 deg	2½ deg	5 deg	5 deg	5 deg	10 deg	Horizon Line
Roll Index						Bottom			Bottom	Roll Limits	
Heading Interval	5 deg Top	10 deg 5:1 Scale Bottom	5 deg Top	2 deg Top	5 deg Top		5 deg Top	Single Mark Top	5 deg Top	5 deg Horizon	5 deg Horizon
Angle of Attack	Fly From	Thermo-meter	Fly To	Moving Index	Fly To			Error	Fly To		
Airspeed	Thermo-meter	Digital, Error		Moving Tape	Moving Tape	Moving Tape	Error	Error	Digital	Digital, Error	Digital, Error
Altitude	Thermo-meter	Digital	Moving Index	Moving Tape	Moving Tape	Moving Tape	Contact Analog, Digital	Moving Tape	Digital	Contact Analog, Digital	Contact Analog, Digital
Vertical Speed	Moving Index	Thermo-meter	Moving Index		Moving Index						

TABLE 30

HUD SYMBOLOGIES

HUD	PERSE-POLIS	CV-193	McD-D	Sperry VTOL	TC-121	Bendix	A-10	MARS HUD	Light Line	VAM	CV-91	MIL-D-81641
Velocity Vector		— —			— —					—	• • •	
Pitch							Digital					> <
Flight Director												
ILS Deviation												
Pitch Ladder Interval	Horizon Limits	1 deg	Horizon Line	5 deg	Horizon Line	5 deg		3 deg	3 deg	3 deg	Single Reference	5 deg
Roll Index		Roll Limits								Not Roll Stabilized	Not Roll Stabilized	
Heading Interval	2 deg Horizon			Digital, Mark Horizon	2 deg Horizon	Single Mark Horizon			Single Mark V/V			5 deg Top
Angle of Attack	Fly From	Fly From			Fly From					Error Optional	Fly From	Fly To
Airspeed			Error	Digital, Error		Error	Moving Tape	Error	Strobing Line	Error		Moving Tape
Altitude	Digital		Digital	Digital	Contact Analog	Moving Index	Moving Tape					Moving Tape
Vertical Speed				Moving Index				Moving Index				

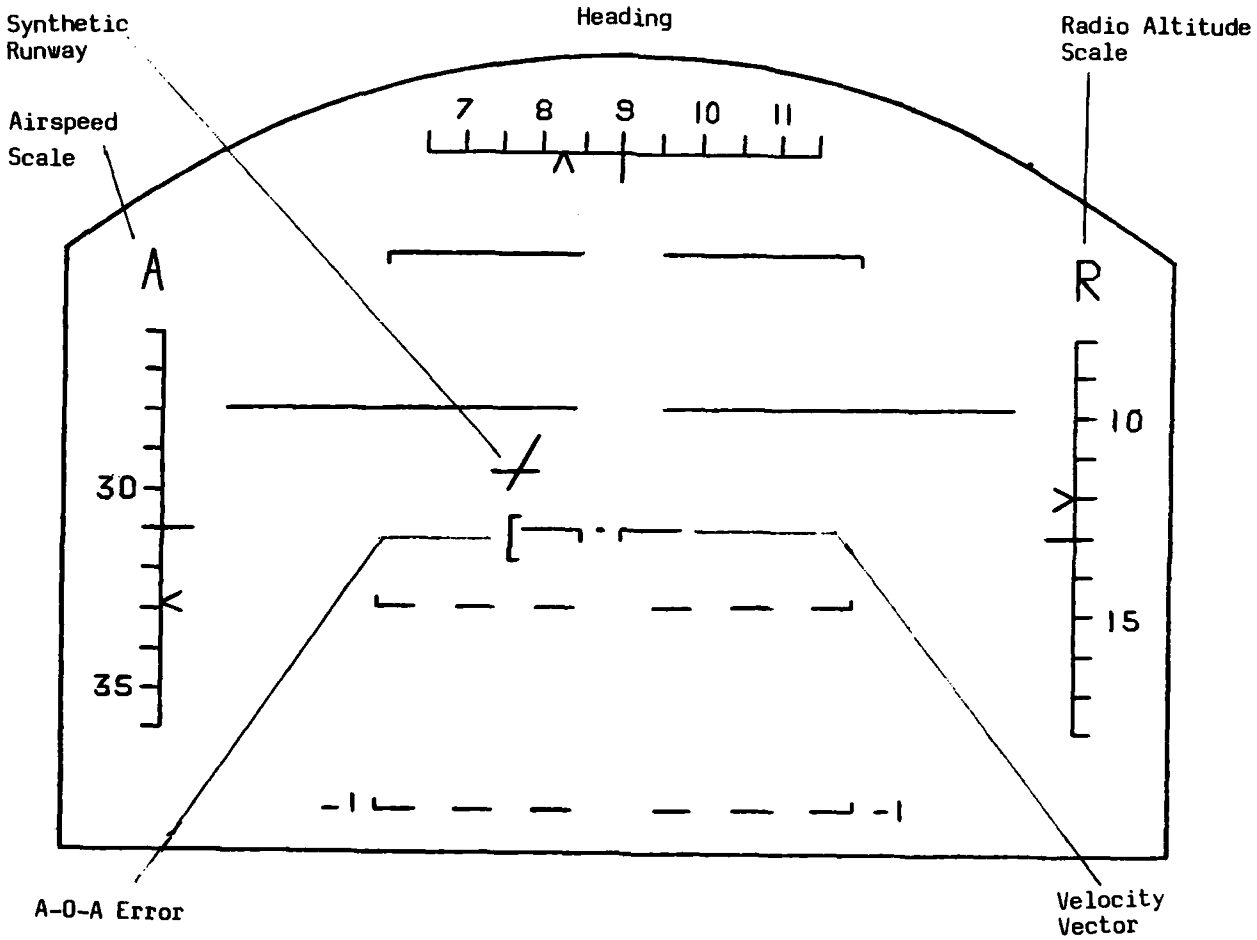
TABLE 30 (continued)



TAKEOFF/NAVIGATION MODE

Figure 3A

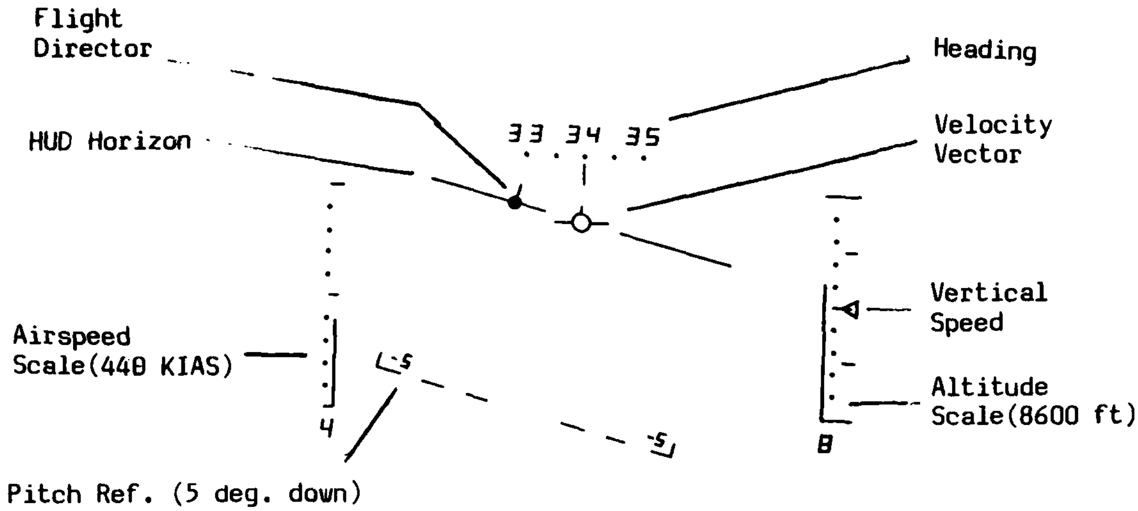
MIL-D-81641 HUD Symbology
(Takeoff/Navigation)



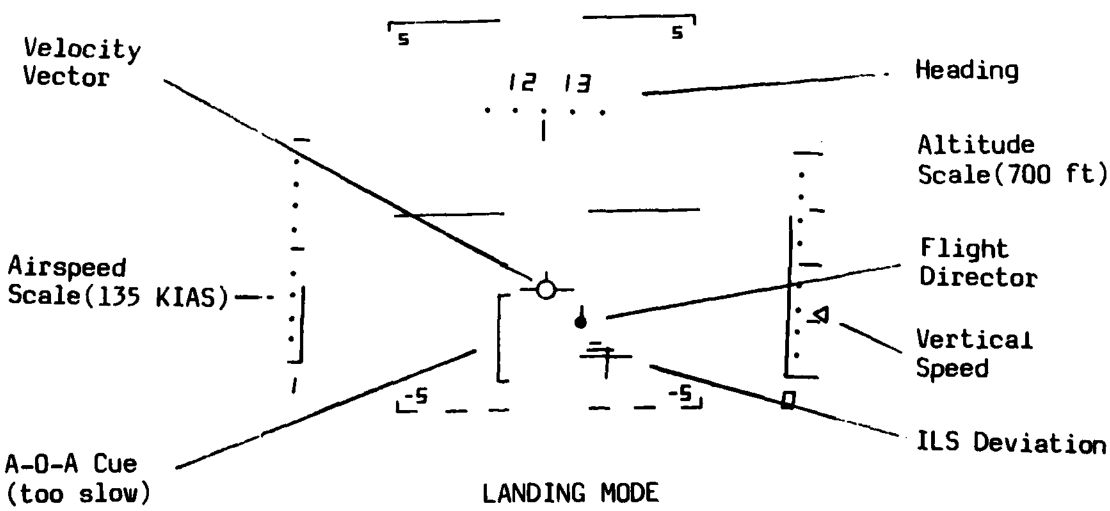
LANDING MODE

Figure 3B

MIL-D-81641 HUD Symbology
(Landing)



NAVIGATION MODE

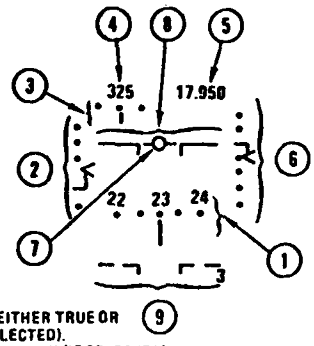


LANDING MODE

Figure 4

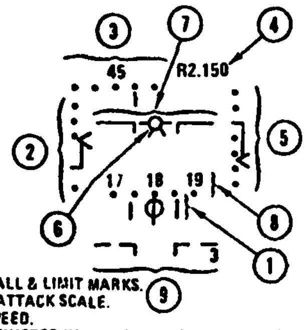
A-7D HUD Symbology
(from Reference 56)

GEN/NAV MODE DISPLAY



1. HEADING, EITHER TRUE OR MAG (AS SELECTED).
2. ANGLE OF ATTACK (IF SELECTED).
3. SPEED ERROR SCALE (IF SELECTED).
4. INDICATED AIRSPEED OR MACH NUMBER (AS SELECTED).
5. BAROMETRIC HEIGHT (SHOWN) OR RADAR ALTIMETER (PREFIXED BY R), AS SELECTED.
6. VERTICAL SPEED SCALE.
7. AIRCRAFT SYMBOL.
8. HORIZON BAR
9. ELEVATION BAR

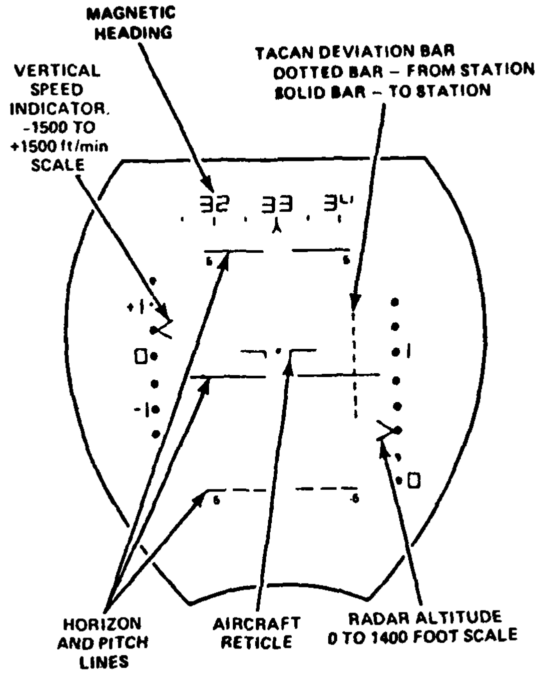
V/STOL MODE DISPLAY



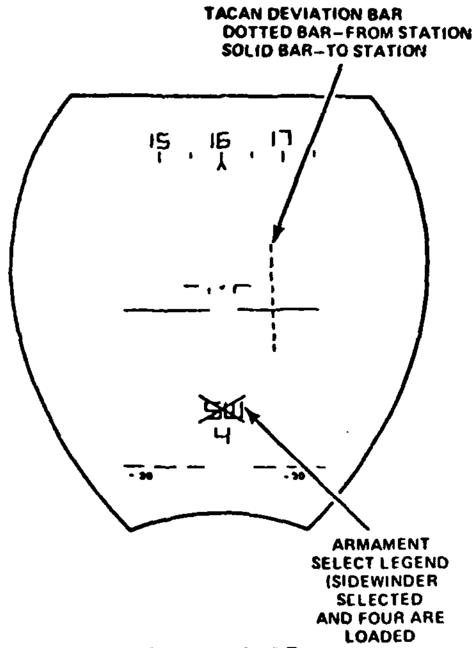
1. SIDESLIP BALL & LIMIT MARKS.
2. ANGLE OF ATTACK SCALE.
3. GROUND SPEED.
4. RADAR ALTIMETER HEIGHT (SHOWN) OR BAROMETRIC HEIGHT (LESS R SHOWN), AS SELECTED.
5. VERTICAL SPEED SCALE.
6. AIRCRAFT SYMBOL.
7. HORIZON BAR
8. HEADING
9. ELEVATION BAR

Figure 5

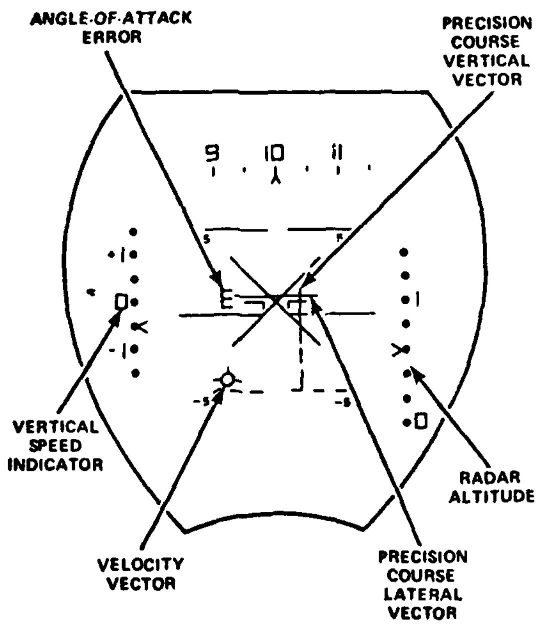
AV-8 HUD Symbology
(from Reference 59)



TAKEOFF MODE



CRUISE MODE
(4:1 Pitch
Compression)



LANDING MODE

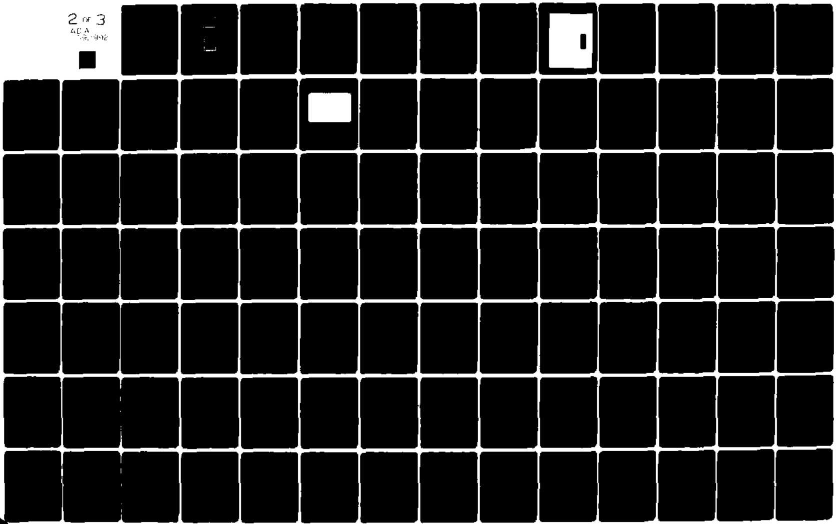
Figure 6

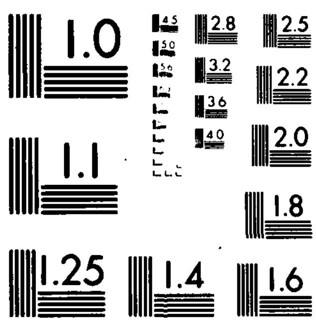
F-14 HUD Symbology
(from Reference 60)

AD-A092 992 CREW SYSTEMS CONSULTANTS YELLOW SPRINGS OH F/G 5/8
OPERATIONAL PROBLEMS ASSOCIATED WITH HEAD-UP DISPLAYS DURING IN--ETC(U)
OCT 80 R L NEWMAN F33615-79-C-0521

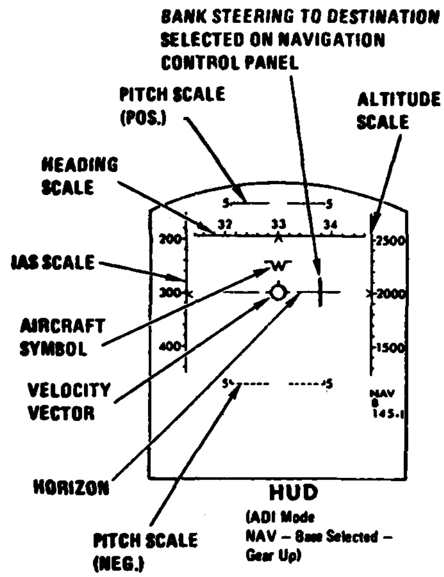
UNCLASSIFIED AFAMRL-TR-80-116 NL

2 of 3
AD A
092992

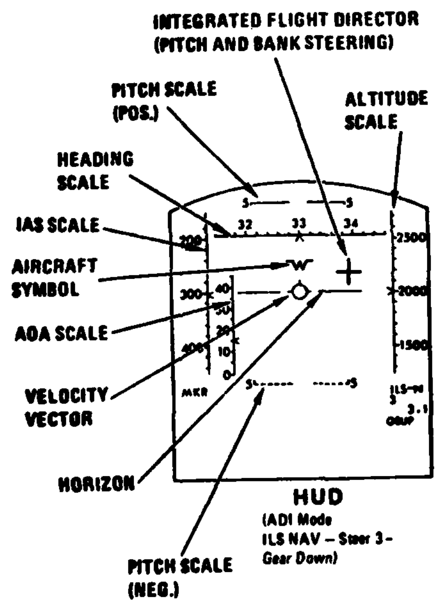




MICROCOPY RESOLUTION TEST CHART



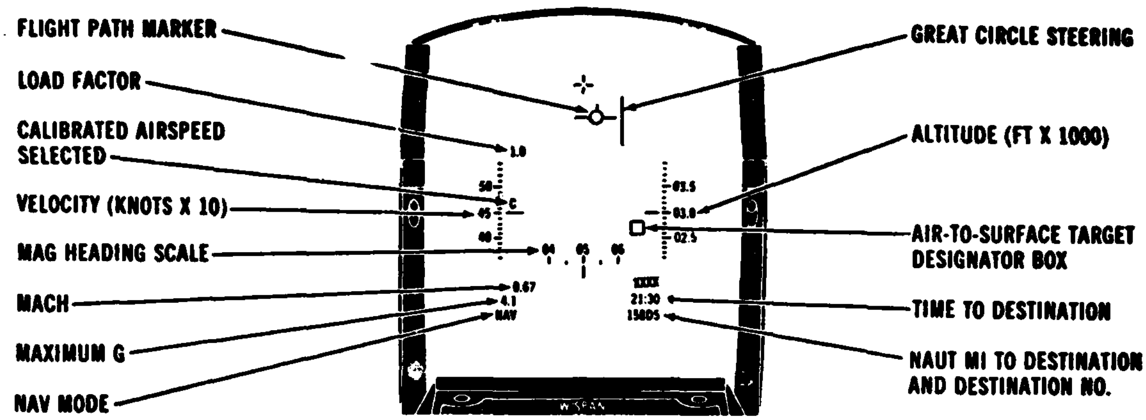
NAV MODE



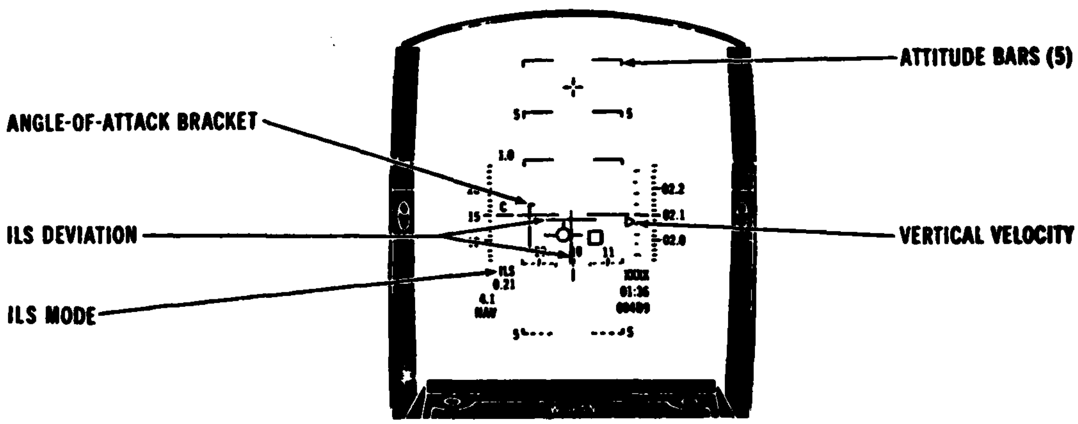
ILS/NAV MODE

Figure 7

F-15 HUD Symbology
(from Reference 63)



NAV MODE



ILS SYMBOLOGY

Figure 8

F-16 HUD Symbology
(from Reference 66)

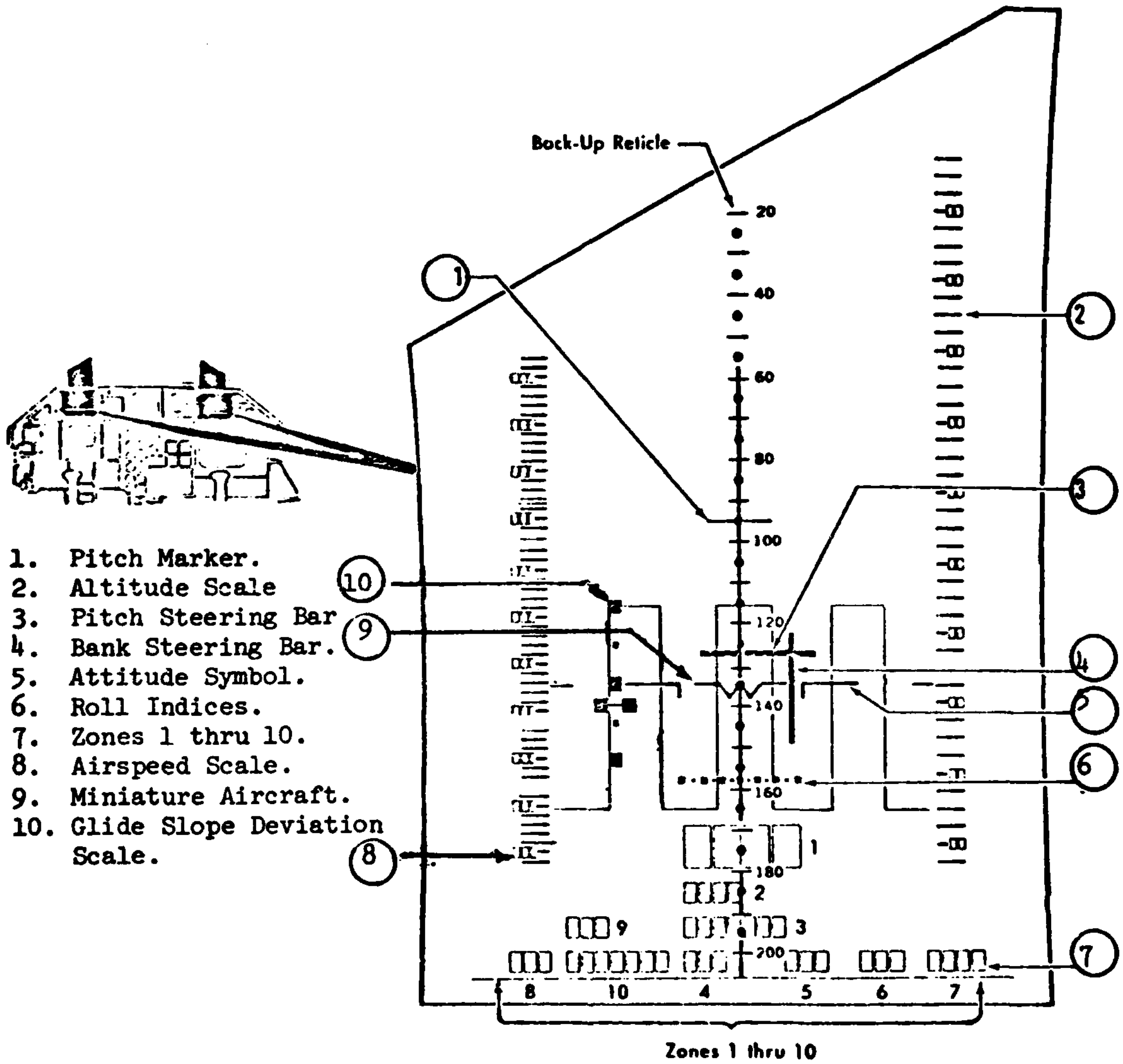


Figure 9

F-111 HUD Symbology
(from Reference 40)

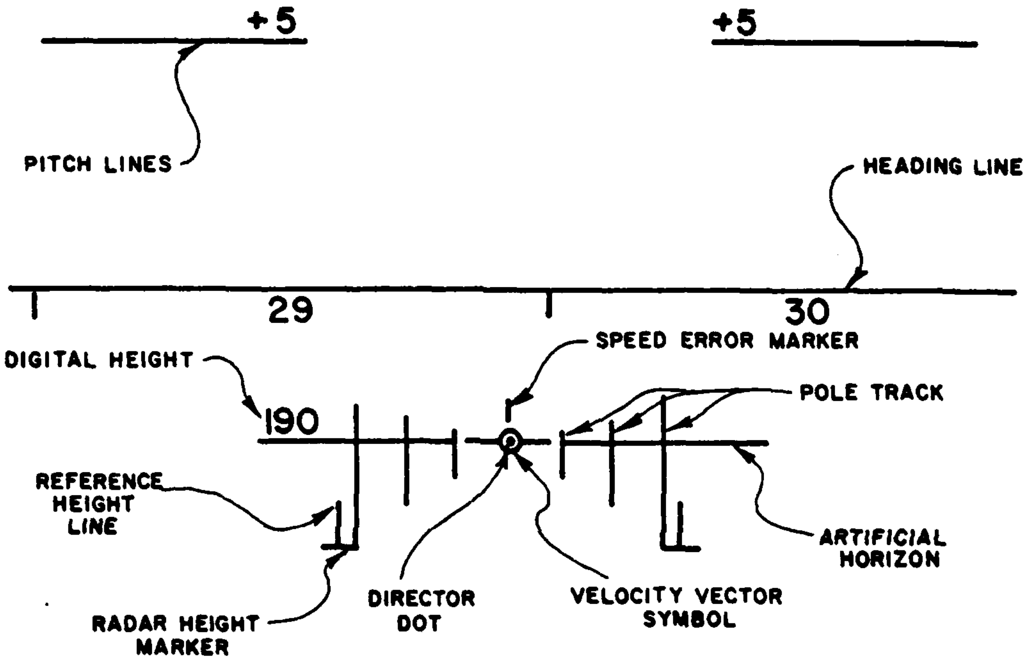


Figure 10

SAAB HUD Symbology
(from Reference 68)

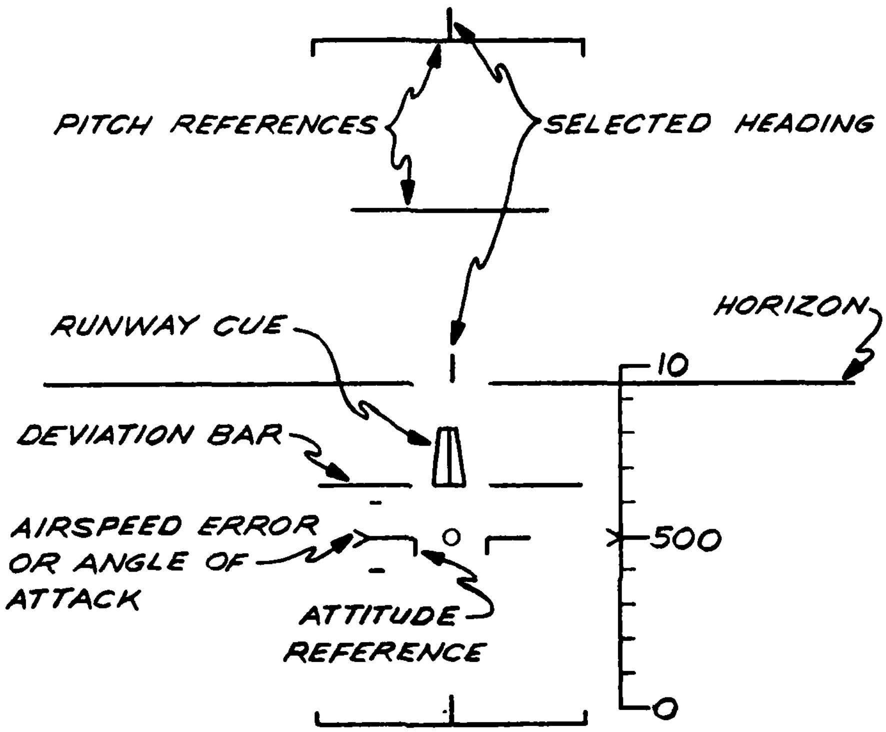
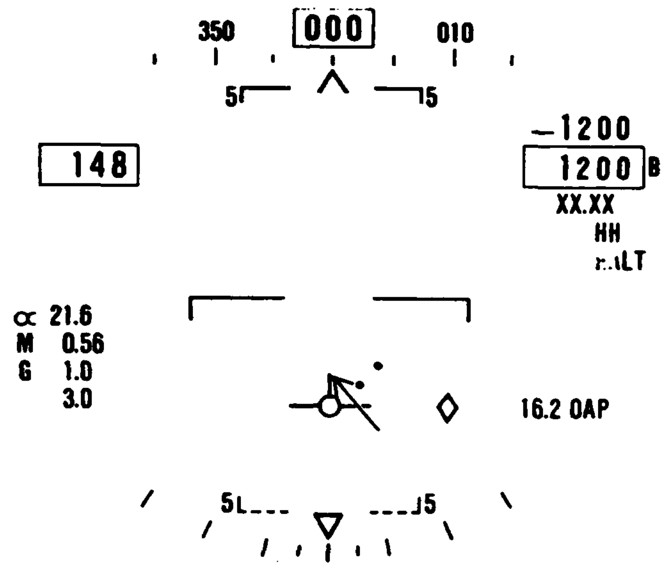
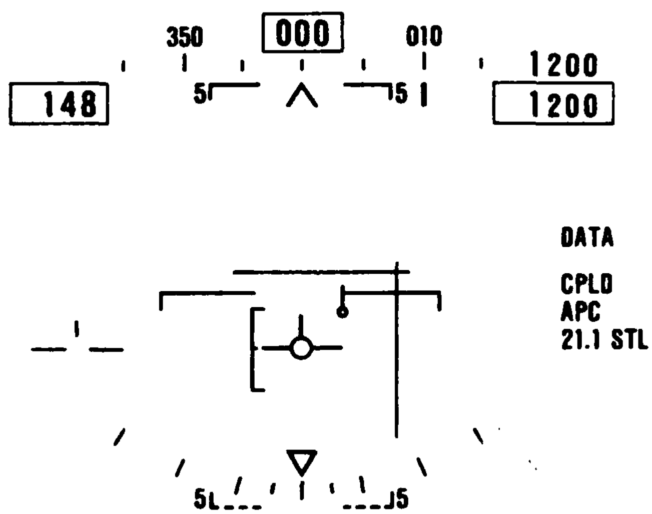


Figure 11

Sperry HUD Symbology
(from Reference 69)



ENROUTE DISPLAY

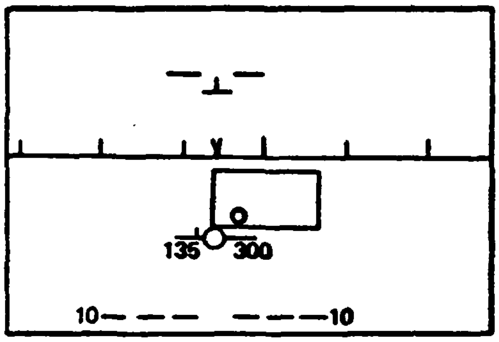


LANDING DISPLAY

Figure 12

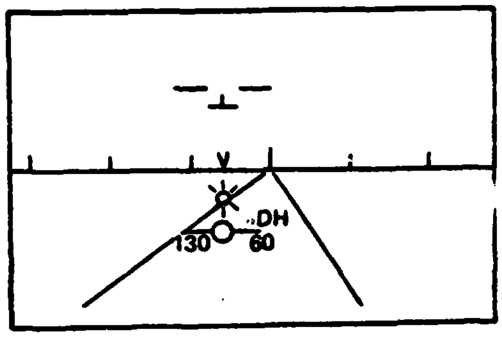
F-18 HUD Symbology
(from Reference 70)

APPROACH



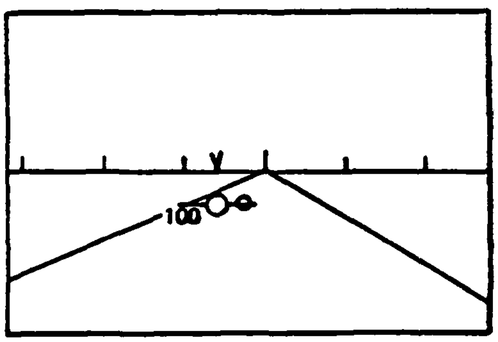
- BASIC IFR SYMBOLOGY
- CAT II ILS WINDOW
- COMMAND DOT PROVIDES FLY-TO-FLIGHT DIRECTOR COMMANDS

FLARE



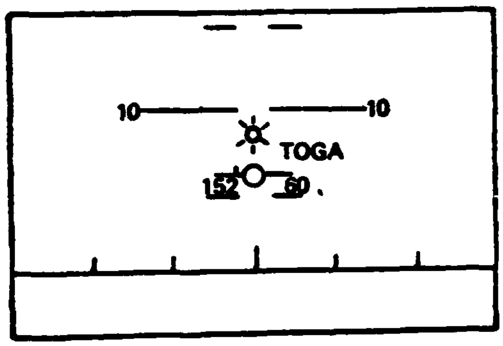
- COMMAND DOT APPEARS FLASHING BETWEEN 60 AND 45 FEET
- FLARE COMMAND AT 45 FEET
- SLOW/FAST BLANKED AT 45 FEET
- ROLL WHISKERS BELOW 100 FEET IF ROLL GREATER THAN 6 DEGREES
- RUNWAY SIDELINES REPLACE ILS WINDOW BELOW 100 FEET
- DH APPEARS FLASHING AT DECISION HEIGHT

ROLLOUT



- COMMAND DOT PROVIDES GUIDANCE TO RUNWAY CENTERLINE
- PITCH SCALE, ALTITUDE AND PITCH REFERENCE BLANKED AT TOUCHDOWN

GO-AROUND



- GO-AROUND INITIATED BY TOGA BUTTON
- COMMAND DOT DIRECT PITCH FOR GO-AROUND SPEED AND HEADING HOLD
- COMMAND DOT FLASHES UNTIL POSITIVE RATE OF CLIMB IS ATTAINED
- SLOW/FAST REAPPEARS

Figure 13

DC-9-80 HUD Symbology
(from Reference 71)

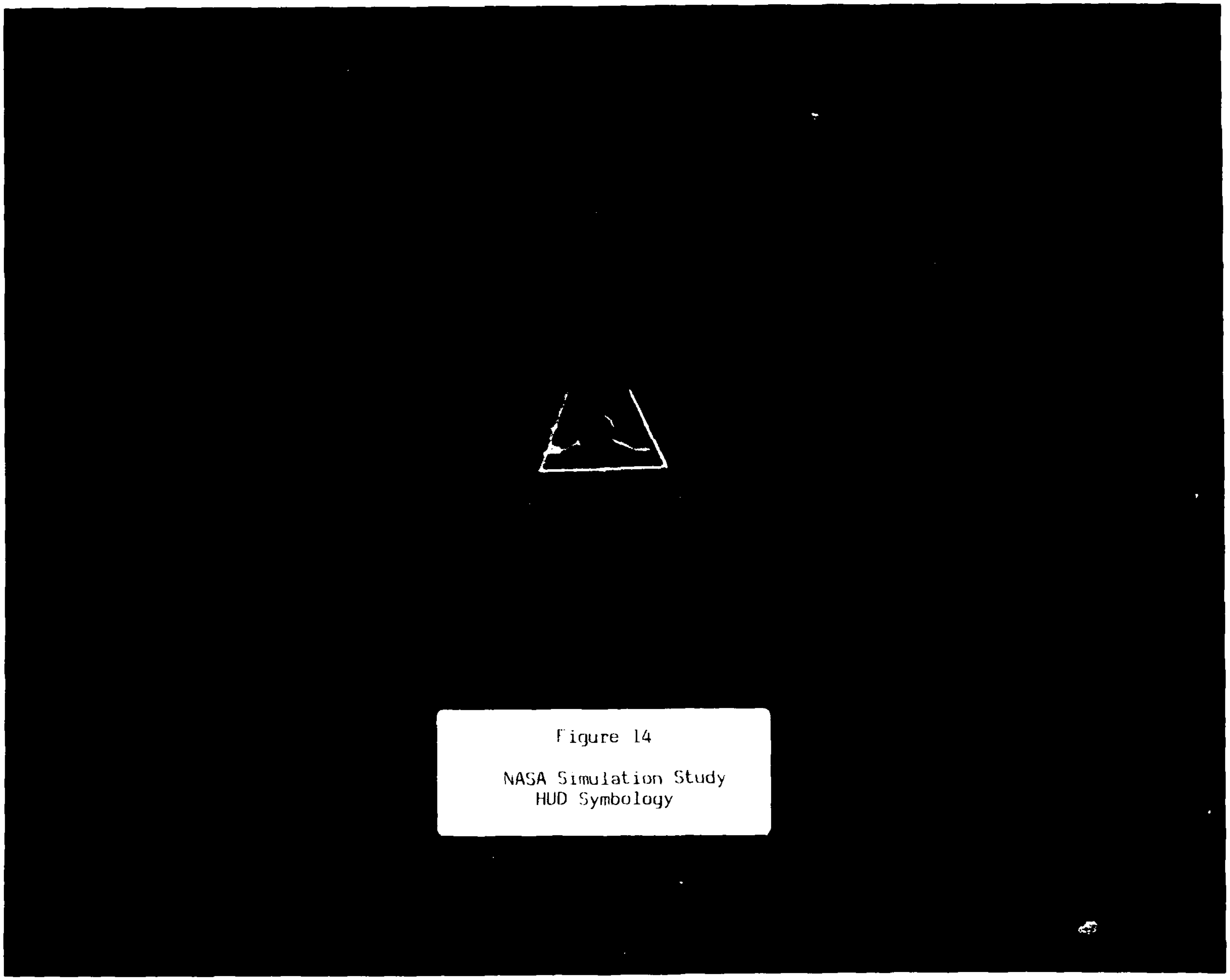
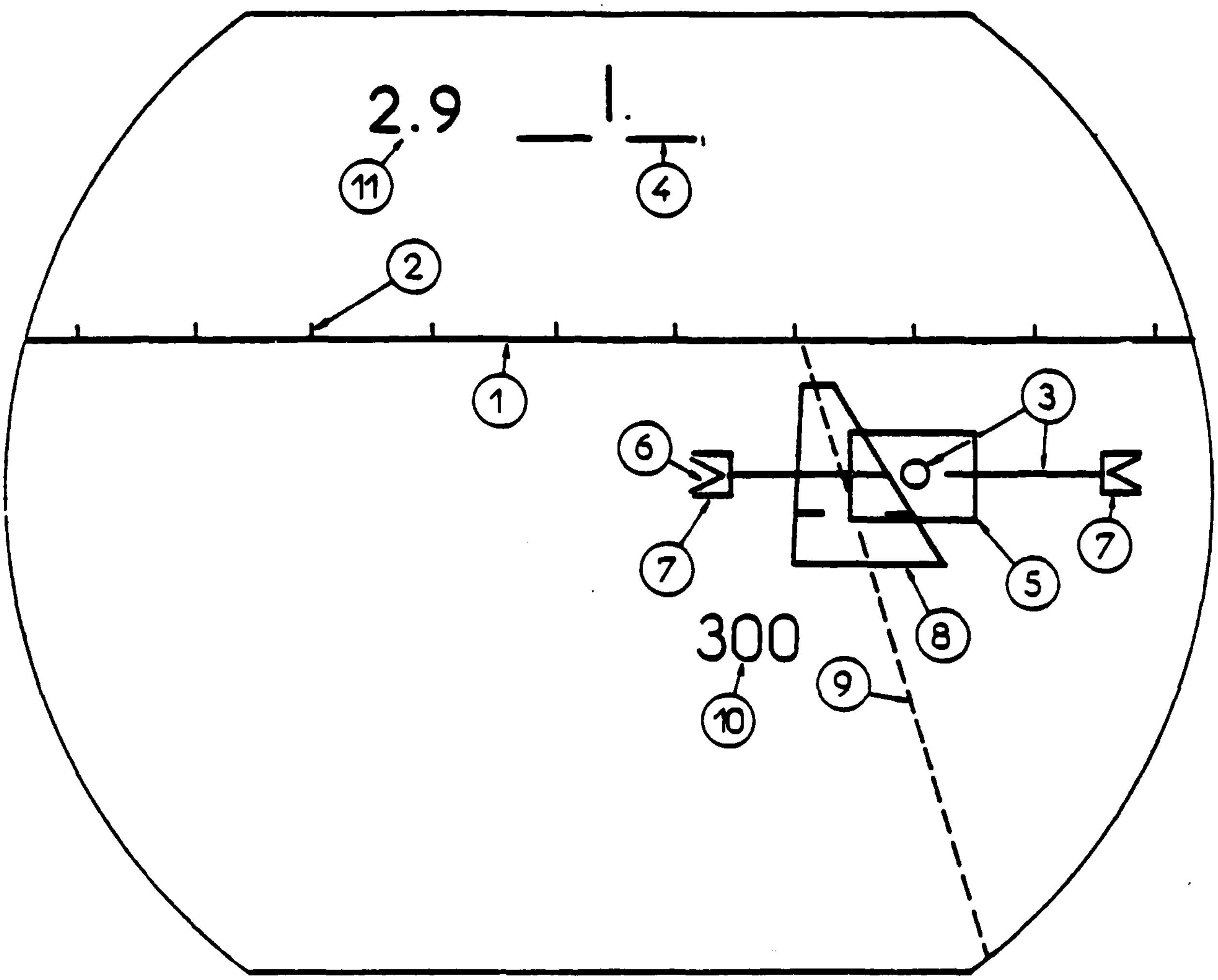


Figure 14

NASA Simulation Study
HUD Symbology



1	Horizon Line
2	Heading Scale (every 2 deg)
3	Aircraft Symbol (Velocity Vector)
4	Fixed Model (Aircraft Pitch)
5	ILS Window
6	Total Energy Symbol
7	Angle-of-Attack Error
8	Synthetic Runway
9	Localizer Axis
10	Altitude (Radio) or Runway Remaining
11	Pre-Selected Flight Path

Figure 15

PERSEPOLIS HUD Symbology
(from Reference 108)

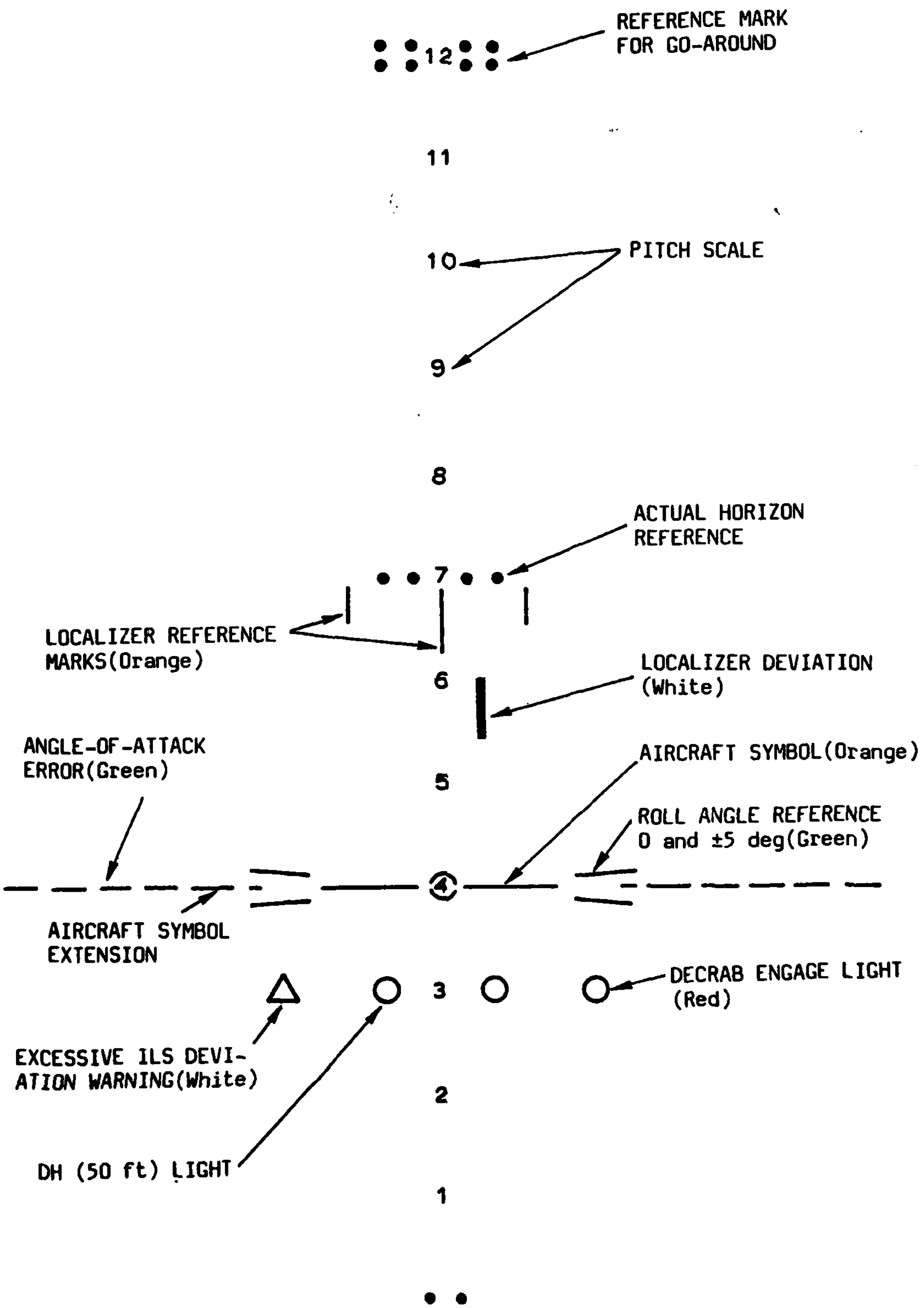


Figure 16

Thomson CV-193 HUD Symbology
(from Reference 73)

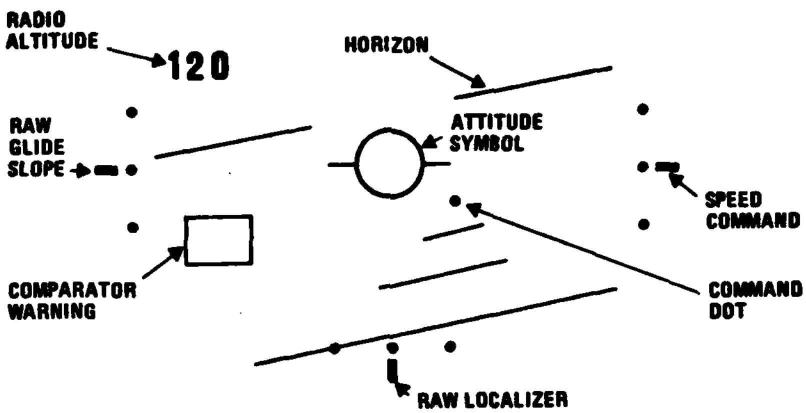


Figure 17

McDonnell-Douglas HUD Symbology
(from Reference 77)

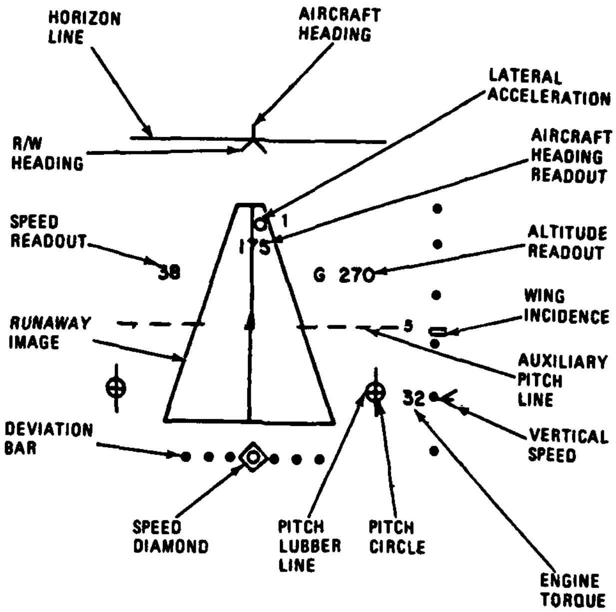


Figure 18

Sperry VTOL HUD Symbology
(from Reference 79)

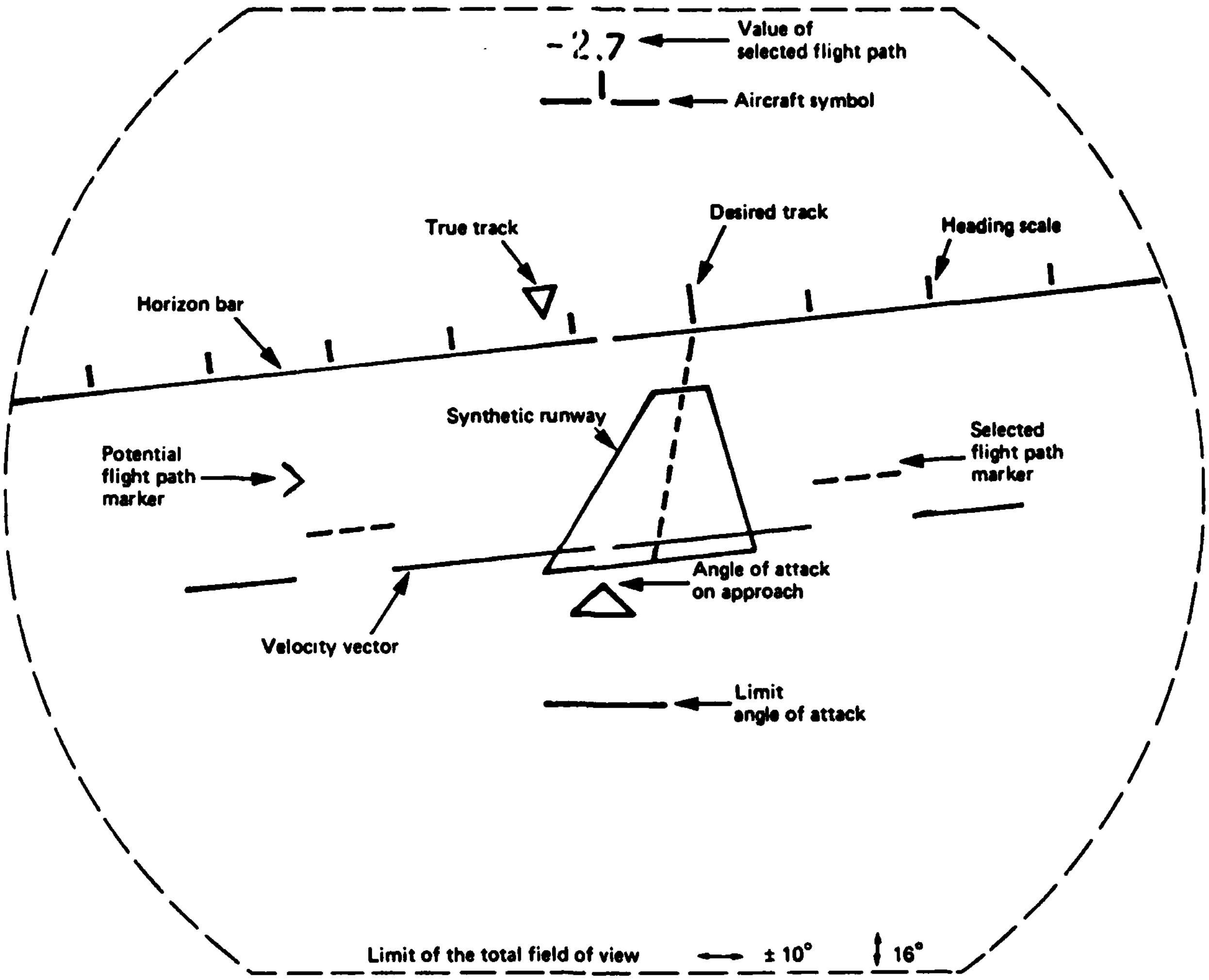


Figure 19

Thomson TC-121 (Klopfstein)
HUD Symbology
(from Reference 82)

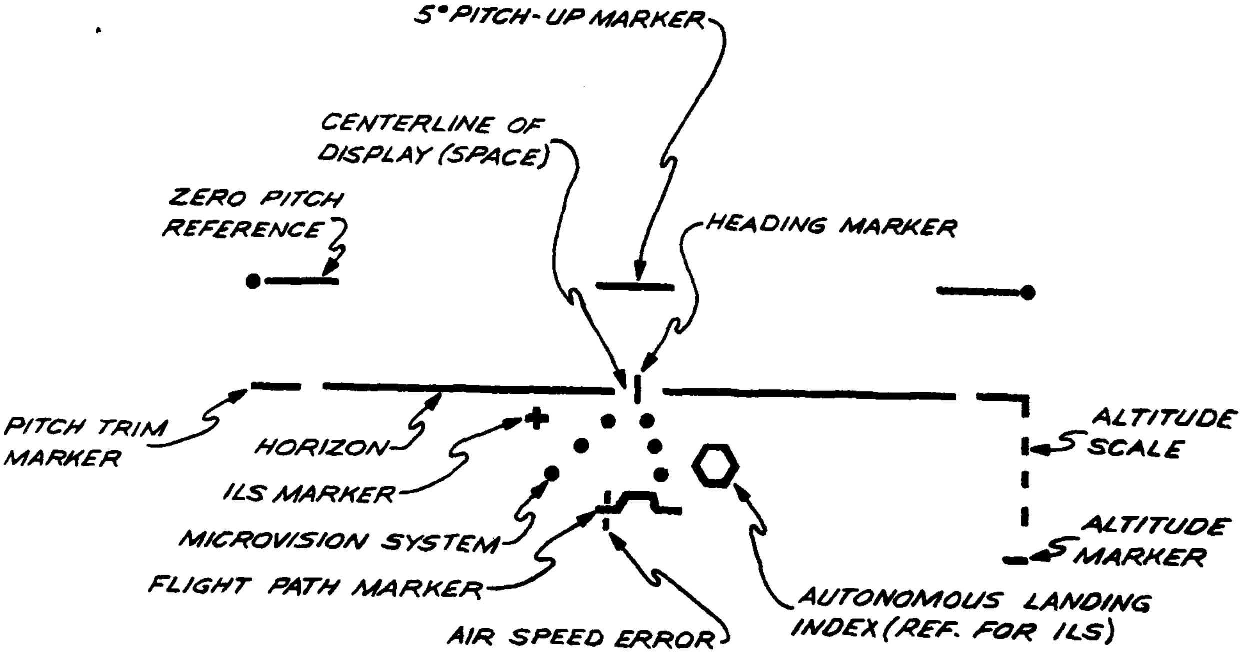


Figure 20

Bendix HUD Symbology
(from Reference 84)

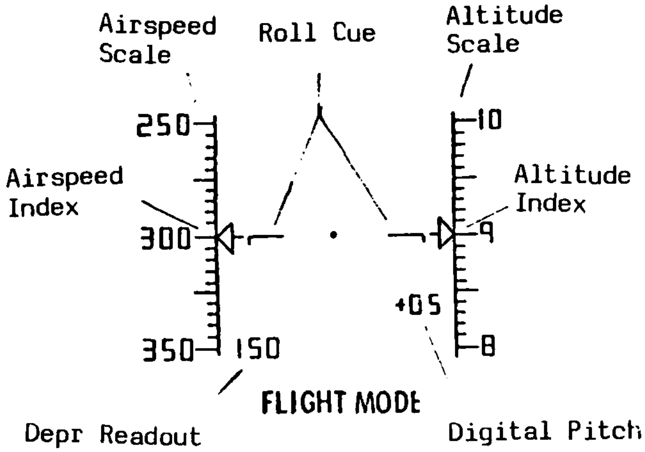


Figure 21

A-10 HUD Symbology
(from Reference 86)

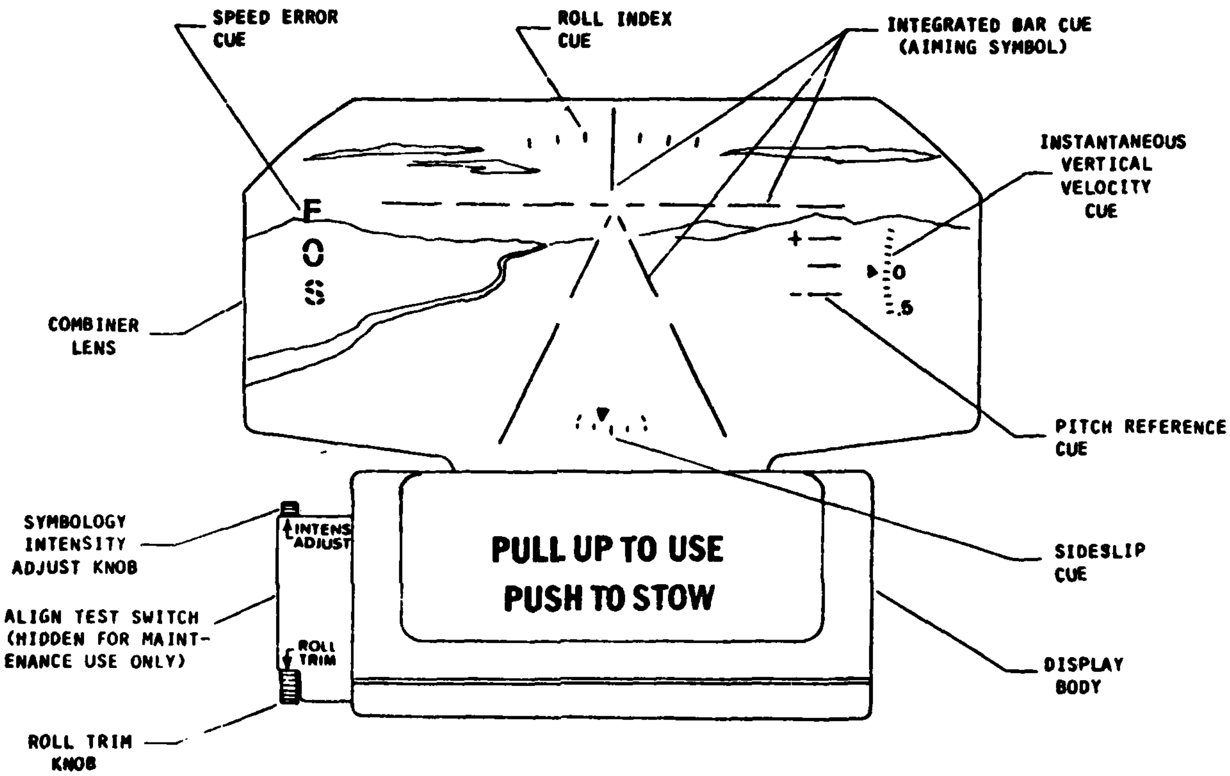
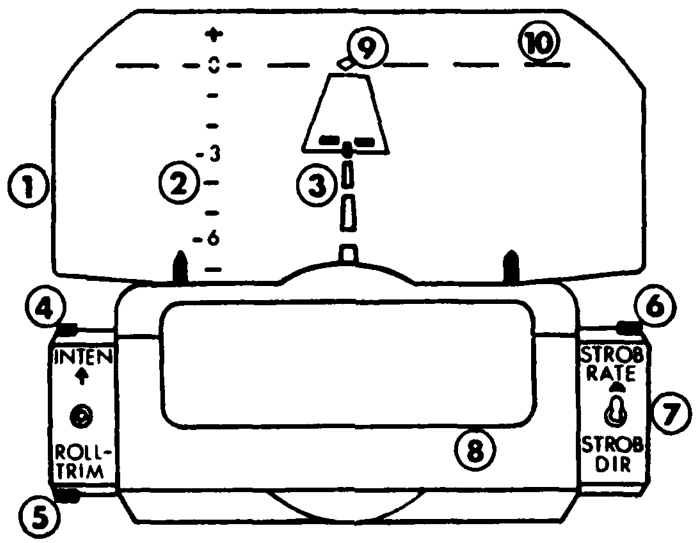


Figure 22

MARS HUD Symbology
(from Reference 43)



KEY:	1	Combiner Lens
	2	Pitch Scale
	3	Light Line (An integrated cue that indicates velocity vector and strobes to show airspeed error.)
	4	Intensity Control
	5	Roll Trim Control
	6	Strobe Rate Control
	7	Strobe Direction Control
	8	Crash Bumper
	9	Aircraft Heading
	10	HUD Horizon

Figure 23

Lightline HUD Symbology
(from Reference 90)

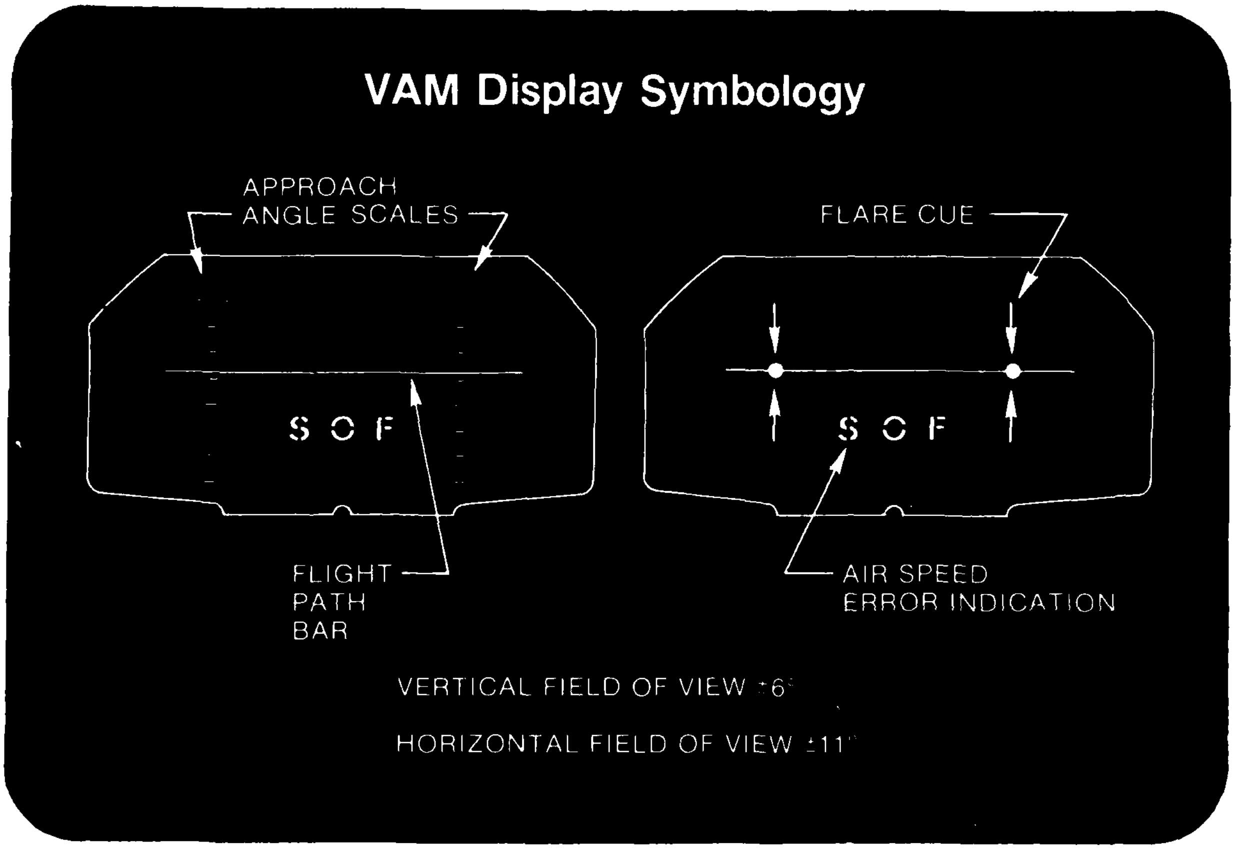


Figure 24

VAM HUD Symbology
(from Reference 94)

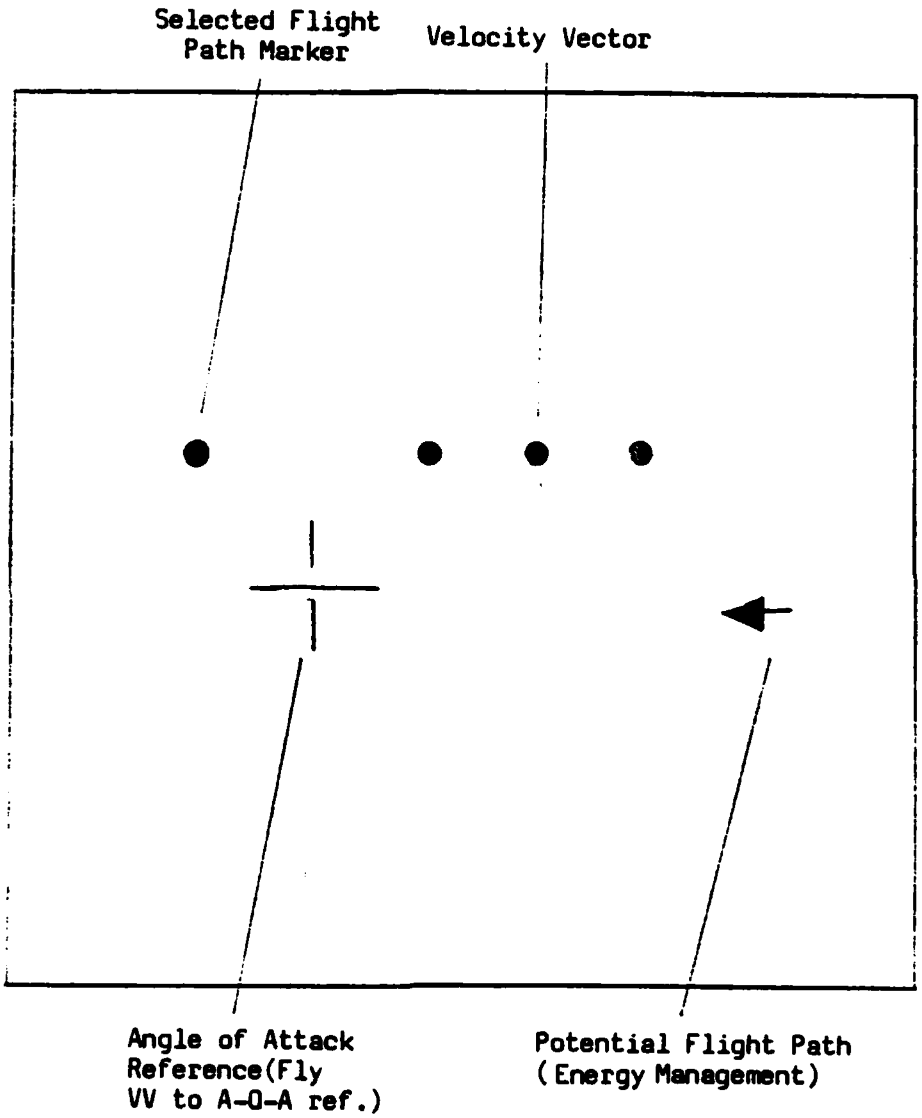


Figure 25

CV-91 HUD Symbology
(from Reference 95)

HUD PROBLEMS UNCOVERED IN SURVEY

SUMMARY

A total of 280 usable responses were received in reply to the questionnaire circulated among experienced HUD pilots. The responses represent a wide range of pilot experience from relatively inexperienced, low-time pilots to highly experienced pilots. The only exceptions to this wide range of experience were the responses from Navy A-7E pilots and Air Force F-16 pilots and from the civilian pilots. These groups appeared to be drawn from relatively experienced pilots. The civilian experience levels, while high, are typical for airline captains.

Assessment of the reported problems show that several problem areas exist for each type of HUD. These are:

A-7D	Vertigo/disorientation in IMC or at night. Behavior of the velocity vector in strong winds. The HUD is too bright at night. The ILS display is unsatisfactory. The angle-of-attack cue is "backwards." Reported insideous instrument failure in IMC.
A-7E	Lack of confidence in the HUD. The HUD is too bright at night.
F-15	The HUD is too dim during the day. The HUD is too bright at night. The design ERP is improper. The altitude/airspeed scales are "backwards." The use of flashing symbols can be missed by the pilot.
F-16	The motion of the display is confusing or disorienting. The display can be too cluttered in some modes. The design ERP is improper. The FOV is too narrow.
AV-8	The HUD is too bright at night. Lack of information in the HUD.

__F-14__ Jitter makes the velocity vector unusable.
The pilots do not use the HUD.

__A-10__ There are several optical problems.
The HUD is too bright at night.
Lack of required data in the HUD.
The pilots do not use the HUD.

__F-111__ The pitch is too sensitive to use.
The glare is too bright at night.
The pilots do not use the HUD.

__B-737__ Lack of required data for flight in IMC.

There are several problems that appear to be common to more than one HUD. These hardware-related problem areas will be discussed in the following sections.

BRIGHTNESS

The brightness specifications appear to be inadequate, both in terms of the HUD being too bright and too dim. Virtually every one of the military HUDs had a large number of complaints and comments regarding being too bright at night. This was reported by A-7D, A-7E, F-15, AV-8, A-10, and F-111 pilots. A common phrasing was "HUD goes from too bright to off." It seems that the minimum brightness range of the HUD intensity control cannot control the brightness range required for night flying adequately. Much finer control of the intensity is needed for nighttime background intensities.

The common approach to this nighttime problem is the night filter. This is a light filter placed in the HUD optics to attenuate the light level from the CRT. This does not appear to be satisfactory by itself. What seems to be needed is a fine-tuning intensity control - at least near the minimum of the brightness range. Perhaps a non-linear intensity control would be the solution.

Only one of the HUDs reported a large number of complaints about the daytime brightness - the F-15 HUD. This may reflect the particular HUD itself or it may be a result of the air-to-air mission of the F-15. There are two other air-to-air airplanes in the survey. One of these was still in testing (F-16) so comments may be incomplete. The other (F-14) had enough other complaints and problem areas so brightness problems may have been overlooked by the responding pilots.* Since the F-15 HUD has a higher level of brightness than some other HUDs in the survey(51), we can conclude that the problem may be an air-to-air related issue and might turn up if we ask additional F-14/F-16 pilots.

Other complaints about HUD brightness were centered on the variations in apparent brightness caused by the automatic intensity control. These relatively few complaints dealt with problems in flying in-and-out of the clouds or when flying over terrain/water features that had widely varying lighting. These complaints were relatively minor in both numbers and degree. The F-111 pilots did complain about the stray glare from their HUD as well as the HUD's behavior when turned off. If the pilot turns the F-111 HUD off at night the entire display "pops" with a bright flow for a short time, effectively destroying his night adaptation.

FIELD-OF-VIEW

Pilots of the F-15 and F-16 HUDs complained about inadequate FOV. While the F-16 FOV is small, this complaint is very likely a reflection of the air-to-air mission of these two airplane/HUDs. The implication is that an air-to-air fighter needs more FOV than an air-to-ground fighter.

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* In addition, only 13 F-16 and 14 F-14 pilots responded, compared with 50 F-15 pilots.

In flying both the A-7 and F-16 simulator, the author did note quite a limitation in instantaneous FOV with the F-16 HUD.

DESIGN EYE REFERENCE POSITION

A number of pilots complained about the location of the ERP. These complaints were most numerous with the AV-8, F-15, and F-16 airplanes, although other airplanes had a few complaints. The problem stems from the desire of the pilot to raise his seat to the highest level during combat in order to maximize his external field-of-view. The HUD design ERP usually seems to have been located by having a fifty percentile pilot sit in the cockpit with the seat at its midrange. When the author (who is 73 inches tall) flew the F-16 simulator, he found that the ERP was too low to view comfortably even with the seat at the bottom.

Two candidate solutions can be proposed. First, the HUD optics could be designed with a variable ERP so that the pilot could adjust it to fit where he was sitting. The second would be to assume that the combat pilot is going to sit as high as possible and locate the design ERP some suitable distance below the canopy and design the seat travel to accommodate the range of pilot sizes anticipated. It should be mentioned that every combat fighter pilot spoken to (HUD experienced or not) agrees with the observation that the pilot will want to sit as high as possible. As one pilct stated in the comments section of the questionnaire, "Somebody should talk to a pilot or two before establishing the design eye."

DISPLAY MOTION

The response of the aircraft symbol (either velocity vector or pitch) does not appear to be adequately controlled by the HUD

specification. In two cases (both using pitch as the primary cue), the display was described as "too sensitive," or possessing "jitter." The HUD specifications do not address this issue, but simply describe the symbols as a "1:1 correspondence with the roll and pitch of the aircraft."(93) No mention is made of the dynamic response of the symbols. It must be emphasized that the description of any display cannot be of a static picture. The relative motion within the display in response to control inputs or disturbances must be shown as well.

The motion of the velocity vector was also cited for those HUDs showing a velocity vector. While the sensitivity was mentioned, the predominant complaint related to the lateral motion of the velocity vector cue. This is a result of sideways drift resulting from either a crosswind or from sideslip. While some pilots reported that this was disorienting, the major complaint was interference with the scales to the side. If the lateral component of the aircraft's velocity vector is sufficient, the velocity vector (and associated symbols that move with it) can interfere with the airspeed or altitude scales. While the HUD specification(93) calls for no interference, this is not the case in practice.

F-16 pilots comment that the velocity vector symbol itself was too "noisy," particularly in its lateral motion. Both the F-15 and F-16 have a "cage" mode where the pilot can command the velocity vector to remain in the center of the HUD laterally while still showing the flight path angle vertically. However, the F-16 HUD does not cancel the lateral deflection caused by sideslip. This creates a laterally noisy symbol.

According to the military standard for electronic and optical displays, the velocity vector is normally damped to make it usable, but

the amount of damping is dependent on the system(97). This same document also states that the velocity vector should show the velocity vector of the aircraft center of gravity (cg). In tests reported by SAAB, the pilot's task is much easier if some display quickening is provided by having the velocity vector show the velocity of a point some distance in front of the aircraft cg(100). In the case reported, a Viggin fighter, a location eight feet in front of the cg was used. This, together with a pitch rate feedback, helped the pilot to control the airplane much more accurately.

It is probably inappropriate for the HUD specification to call for detailed dynamic responses, since the overall response will be dependent on the sensor, on the weapons/navigation computer, and on the HUD mechanization itself. A CRT HUD will have the capability to move any symbol from one point on the display to any other instantly, for all practical purposes. CRT symbol rates are not even limited by the speed of light. What is needed is a system response specification, which at present cannot be defined.

An additional area concerning relative motion within the display is the issue of defining the reference point for the display. Should the zero error point (for flight director commands, for ILS deviation, for airspeed/AOA error) be the center of the HUD, the velocity vector, the center of the horizon, or some other point. This issue will be discussed later in the section on ILS problems.

One final comment concerns "backwards" cues. Two such backwards cues were reported by the pilots, the A-7 angle-of-attack cue and the F-15 moving tape scales. Several pilots reported that the A-7's AOA cue was backwards. In the A-7, the AOA bracket is a fly-from cue, contrary

to the specifications(96,97,101). If the airplane is flying too slowly (at too high an angle-of-attack) the error bracket will be positioned high on the velocity vector symbol. Unfortunately, according to the comments received, most pilots' stereotype response to this stimulus will be to raise the nose, thus aggrevating the situation. All other HUDs using a similar cue, as well as the general specifications, forbid this presentation. It is interesting to note that the A-7 specification itself(101) also calls for a fly-to cue.

The other backwards cue is the combination of airspeed/altitude tapes on the F-15. This HUD has small numbers at the top of the airspeed tape and at the bottom of the altitude tape. As the airplane's nose is raised or lowered, these tapes should move in the same direction. However a significant number of pilots report that either the airspeed or altitude tape is backward. It would appear that they are incompatible.

DISORIENTATION OR VERTIGO INDUCEMENT

Perhaps the most disturbing result of this survey and Barnette's earlier survey(40) is the reported increased tendency towards disorientation or vertigo. Approximately thirty percent of the pilots answered "yes" to the question whether this HUD tended to increase disorientation or vertigo. The figure was higher for those pilots using the HUD extensively in IMC than for those pilots who avoided using the HUD in IMC.

HUD-induced vertigo or disorientation* is reported to result from a number of inflight scenarios. The most common report is an increased tendency while flying in-and-out of clouds. Other instances where disorientation is reported include extreme maneuvers while using the HUD for

* We will use "disorientation" as the generic term in this discussion.

references, such as night pull ups from the target, unusual attitude recovery training, or air combat maneuvering (ACM). A final area of disorientation involves confusing cues while flying the HUD on solid instruments. This is caused by lateral motion of the velocity vector in crosswinds or during ILS approaches.

There may be several factors causing this potentially serious problem in the use of HUDs for instrument flight. The primary cause of pilot disorientation is conflicting cues as to his orientation. According to a review by Tyler and Furr(102), the primary cause of disorientation is reduced visual cues, not an abnormal stimulation of the vestibular cues. What we may see in HUD flying is interference with the instrument cues by confusing or misleading cues from the real world background. This interference may be caused by a number of phenomena - none of which can be confirmed at this writing.

The first possible cause of this interference could be a subtle misalignment of the HUD cues with the real world cues. If the pilot has strong expectations that the HUD cue will overlie the real world cue, any small misalignment may create a reduction in the perceived accuracy of either cue, possibly below the conscious level of perceiving the misalignment. If this is the case, then HUDs driven by INS would appear to have more or less tendency to cause disorientation depending on the threshold level. An INS-driven HUD should be much more accurate than an air-mass-data HUD. However, if the INS still doesn't satisfy the accuracy needs, then the air-mass-data may be better since the pilot won't have the high degree of expectations and will not have difficulty with misalignments. We are also uncertain whether those HUDs which do not provide one-to-one scaling should have more or less tendency toward disorientation.

An experiment to allow the degradation of displayed accuracy from INS quality to air-data quality is the obvious solution to determining if this argument has validity. This could be done easily in existing INS-equipped airplanes, such as the A-7 by disabling the inertial package and reverting to AOA vanes and Doppler inputs. Using research airplanes, such as the NT-33A with the programmable HUD(103), would allow this in addition to examination of the effect of display scale.

Benson cites vestibular nystagmus as an important factor to pilot disorientation.

> On entering a rapid roll or spin, the vestibular nystagmus reinforces the optokinetic stimulus provided by objects in the external scene, which are accordingly seen clearly although the instruments and other objects which move with him (the pilot) may appear blurred. If the maneuver is continued the vestibular signal dies away and the external scene then becomes blurred while the instruments can again be seen(104).

It is not clear exactly what the effect of viewing a virtual image, part of which is stabilized and part not, will be on the pilot.

The effect of head movements in promoting disorientation is well known. The increased head movement necessary to compare the HUD with the panel instruments may be a further complication in the HUDs inducing pilot disorientation.

Framing of the pilot's external view by windshield posts, etc. is also reported to be significant in influencing disorientation(104). While this framing is being reduced in current cockpit/canopy designs (with a possible increase in disorientation frequency), it is not clear if the HUD symbology or even the combining glass edges will provide an adequate substitute. Of possible concern is the F-16 revised HUD which will have the scales float with the velocity vector. What effect this will have is unclear.

Another factor that may be important in causing disorientation by the HUD is the visual background even if no alignment is possible. If a pilot flies through a cloud using the HUD, the background will be seen rapidly approaching him. It is a well known illusion that if we remove this apparently moving background, the surroundings will appear to move in the opposite direction. In our case, the HUD would appear to recede from the pilot. A second factor was reported by Roscoe(105) who likened the problem to the moon illusion. While the HUD is focussed at infinity, the cloud may act as an accommodation "trap" making the pilot's eyes focus at a closer distance. This would make the HUD appear to "bloom." A NASA report is being prepared dealing with this subject at this time, but is not yet available for review(106).

Another factor that could promote disorientation is a general confusing background. In particular a number of F-15 pilots reported an increased tendency for disorientation while practicing unusual attitude recovery with the HUD. In this training exercise,* the airplane is pointed straight up (90 degrees of pitch) until it runs out of airspeed. At this point the airplane departs controlled flight and the pilot must recover the airplane by reference to the HUD. The training is conducted in clear weather in New Mexico. Part of the problem comes from the inability of the HUD to present useful information in the ninety degree pitch up attitude. A second part of the problem is the distracting background for the HUD symbols during the recovery. The rapidly moving background is reported by the pilots to be distracting (rather than disorienting) in both this training exercise and in other situations. Whether this distracting background could lead to disorientation by itself is not known.

* Reported by Major T. D. Albee, 49TFW/DOT, June 1979.

A final disorientation factor was reported by Dobie(107), who stated that pilot confidence in the instruments is a key preventive measure for avoiding disorientation. This may be a factor in HUD-induced disorientation, although it appears that the pilots who mistrust the HUD tend not to use it. The pilots who have confidence in the HUD use it more and appear to report more disorientation problems.

ILS-RELATED PROBLEMS

The display of ILS approach data is a special problem for those HUDs which have this capability (A-7, F-14, F-15, and F-16). The subject is also of vital concern to the potential use of HUDs in transport airplanes for the all-weather approach. In general, the presentation of ILS data in the HUDs does not appear to have been successful. Two descriptions appear common in the reported problems - confusing and hard-to-fly. Two HUDs in particular have received a disproportionate number of complaints, the A-7 and the F-16 HUDs. The problems described for these two HUDs are quite different. The A-7 ILS cannot be displayed without also having the flight director displayed. While the display is relatively easy to follow, the flight director does not provide proper guidance for the pilots to intercept the localizer course. If the flight director is followed, the result will be a series of "S" turns down the final approach course. As a result, most pilots intercept the localizer head-down using the HSI and ignore the flight director until well-established on final. When the author flew a series of ILS approaches using the A-7 HUD, the difficiencies in the flight director were apparent.

The F-16 problems are quite different. The motion of the velocity vector is the source of the complaints. The F-16 pilots felt that the

rapid motion of the velocity vector and the interference between it and the airspeed and altitude scales made the ILS difficult to fly using the HUD. Even with the HUD caged to prevent showing drift, the response of the velocity vector symbol to sideslip inputs was judged to be quite annoying. The problem is compounded by the need to use a different control strategy when flying the F-16 in the landing configuration because of the nature of the flight control system.

The F-15 HUD does not display raw ILS deviation. This HUD shows director commands only. The pilots did not like the absence of raw data. It is not clear if this is a desire for redundant information as a check or because they felt the flight director was not suitable. The F-15 HUD does have two discrete lights to show a fly-up or a fly-down command; which are not particularly desired.

Another ILS problem deals with the use of airspeed/altitude/heading information (the scales). On most HUDs a single on-off switch will select or cancel all of these displays together. Many pilots feel that their HUDs are too cluttered with all scales displayed. However, they often desire one or two parameters at various times during the approach. On an ILS approach, many pilots desired to have the heading displayed during the interception portion of the approach and have an altitude cue during the final portion of the approach. This is not possible on any HUD except the AV-8, where each scale can be selected independently of the others. In particular, the author noted a definite lack of altitude awareness when flying the A-7 HUD with the scales "off" on an ILS approach.

The final ILS-related problem deals with the point of reference for ILS deviation errors (or for flight director errors). To describe this problem, it is helpful to review the error cues that are shown on most HUDs.

<u>Angle-of-Attack</u> Shown by an error bracket adjacent to the velocity vector. The location of the bracket relative to the velocity vector indicates the aircraft speed relative to some desired value. At a constant AOA, the bracket will move with the velocity vector.

<u>ILS Deviation</u> This is a left/right, up/down symbol that indicates the localizer and glide-slope deviation. On most current HUDs this also moves with the velocity vector. However, on some HUDs (and most panel instruments) the deviation moves relative to the center of the display.

<u>A-7 format</u>: For a constant ILS deviation, the ILS symbol moves with the velocity vector.

<u>F-111 format</u>: For a constant ILS deviation, the ILS symbols do not move no matter what the airplane does.

<u>Flight Director</u> This is a left/right, up/down symbol showing steering commands. The same problems arise as with the ILS symbol. However, as the airplane is maneuvered to satisfy the commands, the flight director symbol will decrease to a zero indication.

This relative internal motion, if not integrated properly, can lead to a very confusing display. The F-16 pilots, in particular have complained about this internal motion. When flying the ILS approach in a no-wind condition, there is no problem. However with a strong-crosswind, the velocity vector will be displaced to opposite the direction of the crosswind, for example a right crosswind displaces the velocity vector to the left. If the ILS is shown relative to the velocity vector, it too will move to the left. If the airplane drifts further left, the ILS will show

a deviation to the right of the velocity vector, but to the left of the center of the display.

An earlier survey of A-7D pilots showed that 14 preferred a velocity vector reference compared with one who preferred a fixed reference(42).

The F-16 HUD is being modified to improve its ILS presentation. Besides changing the display gains to dampen the symbol response, the entire display will move within the field of view and remain centered on the velocity vector. Thus, if the velocity vector symbol moves in a crosswind, the scales will move with it. This will eliminate the possibility of interference between symbols. In addition, the ILS deviation will be roll-stabilized so that the glideslope deviation bar will remain parallel to the horizon at all times and the localizer bar will remain perpendicular. This change is an interesting one since the ILS deviation will appear to "rock" relative to the velocity vector wings. According to the pilots, this was a result of confusion during approaches with steep interception turns. Since the F-16 had very little experience in weather approaches when these changes were finalized (almost all of the flying had been done at Edwards AFB), the suitability of this modification to weather instrument approaches remains an open question. The last modification to the F-16 HUD will include a "tadpole" shaped flight director cue similar to the A-7 flight director cue. The introduction of the "new" F-16 HUD symbology into service should be closely monitored.

DETECTION OF HUD STATUS

A number of pilots' comments show their concern with monitoring the HUD status. These comments include concern over HUD reliability, the pilot's inability to readily determine the particular mode displayed, and

concern over instrument failure. Almost all of the responding pilots wanted to have some type of master caution or warning display on the HUD.

Some F-15 pilots commented on the use of flashing displays. In the F-15, in the air-to-air mode, a target designator diamond will be directed by the HUD to show the pilot where the "bogey" is located in his field of view. If the target is beyond the FOV of the HUD, the diamond cannot, of course, line up with it. In this case, the diamond flashes to show the pilot that there is a target, but that it is further out. One pilot commented that, in the heat of combat, he cannot see the flashing and continues looking for the target within the diamond.

Another F-15 pilot commented that he cannot easily detect that the velocity vector symbol is flashing when it is operating in the cage mode. In this mode, the pilot can constrain the velocity vector symbol to the center of the HUD and cancel the display of drift. In the F-15, the symbol will continue to flash to show the degraded mode. While these two examples are from the F-15, other HUDs use flashing symbols as well. (The author had difficulty detecting the flashing symbols in the A-7 HUD during automatic weapons delivery, even though looking for it.) The military standard for electronic displays(97) recommends that the use of flashing symbols be kept to a minimum. The above observations tend to support this recommendation.

The concern over monitoring HUD (and aircraft) status is a real one to operational pilots. This may explain the desire for some apparently redundant information, such as airspeed plus AOA or velocity vector plus vertical velocity. In an interview with one A-7D pilot, he kept insisting on having vertical velocity even though he admitted that he didn't use it

to fly the aircraft. He finally concluded that what he really wanted was some confirmation that the velocity vector was showing the right trend.

We would certainly recommend that automatic HUD mode change be kept to a minimum and, if necessary, clearly annunciated. Obviously, the same symbol should not be used for two different purposes.

The problem of a "caged" velocity vector is interesting. This option appears to be of value to the F-15 and F-16 pilots, even though the use of a flashing symbol is not adequate to detect the submode. It would seem that a different symbol and a different terminology should be used to describe the flight path when drift is not available or not desired. We would propose to use the term "flight path angle (FPA)" to describe this. Several HUDs already use such a parameter, although called by different names and using similar symbols. The Thomson-CSF TC-121 (Klopfstein) HUD is a good example of such a HUD. Its dashed horizontal line is appropriate for this "driftless" or caged velocity vector.

The detection of faulty or degraded information is also of concern. While pilot training is a key issue in this regard, the HUD itself should be designed to ease the pilot's task. Adequate internal failure monitoring must be supplied. In this regard, EM HUDs are easier to monitor than are CRT HUDs, since a mechanical sensor may be placed in the EM display to physically detect its location. This is not possible with an electron stream in a CRT.

UNRESOLVED ISSUES

A number of issues remain unresolved at this point. These questions could not be answered from the questionnaire or from interviews with A-7D pilots at the 178th TFG. These issues are vertigo/disorientation, data presented on the HUD, display dynamics, ILS interpretation and procedural issues.

Vertigo/Disorientation

The questions here are the effect of the background, the effect if misalignment of the HUD data with the real world cues, and the effect of motion within the display. This can best be conducted in-flight using a tactical-type aircraft with a programmable HUD. While the experiment could be performed in a simulator, the duplication of motion and external visual cues would be difficult to accomplish and would, in any event, require in-flight validation.

Information Presented on HUD

Several questions are raised in this area. The first question is what scales are desired by the pilots and what declutter options should be used. As mentioned before, several pilots have criticized the present all-or-nothing approach to display or reject the scales. Should the scales selection be automatic, much as it is in the F-15? Should the individual scales be selectable, such as in the AV-8? This question can best be resolved by means of a follow-up questionnaire, and possibly subsequent simulation studies.

The second question raised concerns the type of display - moving tape or digital.* The AV-8 presently has digital airspeed and altitude.

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* Other display formats (such as the A-7D/E thermometers or moving scales) do not appear to be likely candidates.

There were a few comments in the survey that indicated that one or two pilots could not obtain rate or change data from these digital displays. A follow-up to AV-8 pilots is warranted to see if this is real or just noise in the survey results.

As mentioned before, several pilots commented on their desire for redundant information. Additional information is needed to decide if this is a training problem or should be addressed in HUD design. The problem with adding more parameters to the HUD is, of course, clutter. At the same time, we need to determine if the pilots can or cannot readily detect what mode the HUD is displayed in the HUD.

Display Dynamics

This issue is closely related to the topics discussed in the subsection on vertigo/disorientation. In addition to determining the susceptability of the pilots to disorientation because of the HUD, we need to investigate if the dynamic response and display accuracy are significant. This issue has been addressed in the past in simulators, but must be studied inflight. At this point, ground-based simulators are simply not suitable for accurate duplication of the visual and kinesthetic stimulations accompanying flying an airplane. The military standard agrees in principle(97), but simply states that the velocity vector should be damped. One of the questions raised at the beginning of this study was what is the interaction between airplane dynamics and HUD dynamics. As we have seen, no information is available to determine what the HUD dynamics are for our present day HUDs. We need to determine the overall response of the HUD (and airplane) to specific control inputs and measure the HUD response. Then by varying the HUD dynamics and/or the airplane

dynamics, we can determine if there is any correlation. At this point, we have shown that there is a problem. Now we must quantify it.

This has been done before, usually in simulators. What is needed today is to duplicate "good" airplane/HUD combinations, such as the A-7 and compare the dynamics with "bad" airplane/HUD combinations, such as the F-14 or F-16. This could be done with either actual line airplanes or using the AFFDL NT-33A variable stability airplane.

ILS Interpretation

The issues here are: (1) How does the pilot use the HUD? (2) What orientation should the data be in (referenced to the aircraft datum line or to the velocity vector)? (3) What is the use of the flight director? and (4) Can pilots using a HUD maintain a sense of altitude awareness? Part of these questions need further amplification by line pilots presently using HUDs. There needs to be a follow up interview/survey of those pilots using HUDs today concerning ILS issues.

In addition, a very serious question has been raised by Naish(6) and more recently by Fischer, et al(38). The question is, What will a pilot do if the real world cues and the HUD cues diverge during breakout following an ILS approach? Both workers used a simulation study to attempt to answer this critical question. In both studies, pilots were asked to fly an instrument approach to minimums and breakout, completing the landing with visual reference to the runway. During the course of both experiments, the HUDs were misprogrammed to lead the pilots to an off-runway landing. Both experiments studied lateral deviation errors only. In both cases, the pilots, upon breakout, ignored the HUD and completed the landing solely by reference to the "real" world cues.

Because there are several visual illusions that occur during breakout from a low visibility ILS approach, this may not be what we want the pilot to do. Since most of these illusions cause deviations in the vertical rather than the lateral direction, the Haines or Naish studies may not have addressed the critical issue. For the sake of argument, let us hypothesize that a pilot breaks out following a low visibility approach and observes a vertical deviation in the real world cues and the HUD cues. Let us assume that the real world cues tell him that he is going to land long and the HUD indicates he is going to land short. What would he believe? Which should he believe? Both of the studies cited imply that the HUD will be the cue in error. This may be true in the directional case where the cues are more easily interpreted than in the vertical case. Most pilots are well aware of the possibility of visual illusions that will cause them to misjudge an approach - in fact the HUD is intended to prevent this. We are not sure what the pilot will do and we are not sure what we want the pilot to do, other than go around and decide the answer at a safe altitude.

Two other in-flight studies may have bearing on this issue. In the MARS HUD evaluations(21,43,44), visual illusions may cause the recovery aircraft to fly into the parachute. The HUD was intended to prevent this. During the evaluations of the helicopter HUD in southeast Asia, the pilots commented following one sortie that they had a strong illusion that they were much too low, but that having confidence in the HUD, they believed it and made a recovery in very difficult circumstances. During the CH-130 evaluations, the HUD was deliberately misprogrammed to create diverging cues. In this case the pilots again followed the HUD causing several parachute/airplane collisions.

While these MARS missions are not ILS approaches, they do indicate opposite conclusions from the two simulator studies. That is, pilots will believe the HUD rather than external visual cues. Will this happen in an ILS approach, particularly with vertical disparity between the real world and the HUD cues?

The NASA simulation study, previously discussed, also presented the subject pilots with an obstructed runway showing a DC-10 taxiing in the touchdown zone(38). The pilots flying using HUDs took longer to detect the other airplane than pilots flying without a HUD. Two of the subject pilots using the HUD failed to perceive the airplane at all in spite of the oculometer showing them looking at it and its image completely filling the central parts of the HUD. While this result may be a peculiarity of the simulator situation, the implications for using HUDs in routine landings are serious.

An objection to this study may be the lack of HUD experience and confidence by the subject pilots. To counter this, the experiment should be repeated with experienced Air Force HUD pilots.

Procedural Issues

Three questions remain unresolved in the area of HUD procedures: How do the pilots use the velocity vector? What difficulties are there in transitioning from a head-up velocity vector presentation to a head-down pitch reference? and several questions in the training area. The use of the HUD in training will be discussed in a later section.

The question of the techniques for the pilots to use the velocity vector was amplified by the two A-7 pilots who, after over one hunderd hours in the airplane, have developed difficulty in using the velocity vector. It would indicate from this that the initial training is

incomplete since the pilots don't have a clear understanding of the meaning of the velocity vector and also that the flight manual procedures are not adequate to supplement the initial training.

A clear understanding of the relationships between velocity vector, pitch attitude, airspeed, vertical velocity, and thrust is essential for the pilot to be able to fly the airplane consistently. However, the best techniques to control these various parameters given the particular display are not presented to the pilot. It would be interesting to see if F-15 pilots (who have a pitch reference in their HUD) have fewer problems with either the techniques or with the head-up/head-down transition.

TRAINING ISSUES

It was apparent during the course of this study that very little attention is being directed to the initial (or recurrent) HUD training for the military pilot. The overwhelming observation is that the problem is ignored in both the Dash Ones(56,59,60,63,66,86) and in AFM-51-37(39). The general approach is to provide a brief description and a short cockpit orientation of the switch locations.

ORGANIZATIONAL ATTITUDES

A significant problem with the use of HUDs may be the organizational attitude of the units involved. A significant number of F-14 pilots commented that the training cadres at the replacement air group (RAG) wing were quite negative on the use of HUDs. By contrast, the A-7D pilots of the 178th TFG (studied in the training survey) enjoy a strong pro-HUD attitude by their command.

Attitude problems are not helped by warnings in the Dash One, such as:

> CAUTION
>
> The HUD is not a primary flight instrument; accordingly its flight data should not be used as a substitute source of information to the airspeed indicator and altimeter for takeoff and landing(86).

which seem to imply that the HUD should not be trusted.

Part of the difficulty lies with the IPs used for initial checkout and the squadron level training staff. These groups need to encourage

the pilots to use the HUD and train them to use it properly without causing over-reliance on it.

Unfortunately, when a new unit receives HUD-equipped airplanes for the first time, the more experienced, older pilots will be the training cadre. According to the commander of such a squadron,* it may take them up to 300 hours flying time to feel that the HUD is a help and to really learn how to use and teach the HUD. Obviously, the training imparted to the other pilots in the squadron may suffer during this extensive period of adaptation by the more experienced pilots.

Extra care must be taken to ensure that sufficient encouragement from above is applied to overcome any reluctance or uncertainties with the use of the HUD by pilots during initial checkout. This, of course, must not blind management to any deficiencies in the equipment.

FLIGHT CONTROL WITH THE HUD

Use of the Velocity Vector

HUDs have introduced a new dimension into flight control - the use of velocity vector to replace or supplement pitch cues. This concept is a new one to most pilots and may not appear to be natural at first. One A-7 pilot likened it to a "garden hose that may go up or down as you raise the nose." This may create difficulties to those pilots trained in attitude flying.

Unfortunately, many pilots do not realize that they don't understand the difference between flight path angle and pitch reference citing

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* Col. Robert Preston, Commander 178th TFG, Springfield ANGB, Ohio, August 1979.

difficulties when a change in pitch doesn't affect flight path angle or "I know I'm nose high, but the velocity vector shows level flight."*

Several pilots also mentioned difficulties in switching from a head-up velocity vector reference to a head-down pitch reference. Perhaps the incorporation of the pitch symbol (as on the F-15) helps this adaptation from head-up to head-down. As an alternative, the evaluation of a suitable flight path angle indicator for the instrument panel should be assessed. In spite of the negative conclusion reached by Barnette and Intano(108), the concept has not been tested in a realistic environment with pilots fully trained in its use.

An interesting observation was reported by the ALPA HUD Newsletter. This article reported that Navy A-7E pilots fly better night carrier approaches without a HUD than A-7A (no HUD installed) pilots(109). The conclusion is that using a HUD makes better pilots even after taking it (the HUD) away. Possibly this results from improved understanding of the relationships between flight path angle, pitch, airspeed, power, and vertical speed simply by using the HUD for some time.

Operational Procedures

Operational procedures compatible with the actual parameters displayed must be written and included with either AFM-51-37(39) or in the Dash Ones. This problem is especially noticeable with the F-16 in which the stick commands AOA and the HUD displays AOA and vertical velocity. F-16 pilots have reported that this requires special procedures "unique to the F-16" to avoid chasing AOA and velocity vector.

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* An A-7 test pilot interviewed at LTV in October 1976. Unfortunately, his name has been lost to posterity.

The need for a bank index comes from the procedures in AFM-51-37 and previous attitude flying experience. Either the bank index should be provided or the references to specific bank angles deleted.

INSTRUMENT CROSS-CHECK

Many pilots commented on difficulties with cross-checking other instruments while flying with the HUD. Apparently, many of the HUD studies cited earlier have only considered part of the pilot's task - that of flying the airplane. The pilots must also act as a systems monitor and as an aircraft commander(45,110). This means that he must be kept aware of the aircraft status and of any malfunctions (systems monitor) and that he must exercise a high degree of positional and altitude awareness (aircraft commander). This is particularly important for the pilot of a single-seat airplane, although it must be addressed in multi-crew airplanes as well.

Sufficient redundant cues must be available for the pilot to satisfy himself that he is flying with valid data. For example, if the altitude is increasing while the velocity vector shows three degrees down, the pilot would very likely conclude that one was in error. Although it would be nice for him to be able to ascertain which one, the important point is to allow him to cross-check and see that they disagree, that there is a problem.

Lacking adequate cross-check capability, some reliable failure monitoring system is required. We cannot ignore this problem by silence on advising the pilots not to use the system in critical situations, since pilots will use the HUD if it helps their flying.

Altitude awareness is a problem with today's HUDs during ILS approaches. If the scales are rejected to minimize clutter, no altitude is available on the HUD. Subjectively, we find that even with scales selected, there is a tendency to concentrate on the central portion of the HUD. A pull-up anticipation cue similar to the weapons delivery cue could be quite beneficial.

SPECIFIC HUD TRAINING

Use of the HUD has several facets that must be addressed during training. The student must be taught where and how to look at the specific cues of interest. He must also be shown how the HUD responds to control inputs or outside disturbances. This can best be accomplished in a simulator or a HUD part-task trainer. The initial HUD indoctrination must ensure that the student understands and trusts the HUD.

The instructor must also have the capability to see what the student sees in the HUD either by a video monitor or other means. This includes the view of the external scene. He (the IP) should also have an override capability to delete items or to adjust the brightness. A separate, instructor-controlled cursor to point out items of interest to the student would be helpful. While this could all be done in-flight, obviously a two-seat airplane would be required. It would also be difficult to give the IP a view of the real world in the rear seat of a tandem seat airplane.

As a final, confidence building exercise, a HUD-only sortie should be flown.

The HUD would also be extremely useful during undergraduate pilot training (UPT) as a means of demonstrating the different concepts of

pitch, angle-of-attack, flight path angle, and other related parameters. In this case, the HUD should be under the IPs control and the use of the HUD controlled by the syllabus.* If the argument that exposing pilots to a HUD with a velocity vector improves overall pilot competence, the case for a UPT HUD is self-evident. Although concern about the student becoming over-dependent on the HUD has been expressed, the opposite reaction may well be true.

* To preclude the student becoming over-dependent on the HUD, a lock-out could be incorporated to disable the HUD on solo flights.

STANDARDIZATION

While the subject of standardization was not addressed in the questionnaire survey directly, the issue of HUD standardization cannot be avoided. We have already remarked that there is considerable variation from HUD to HUD, both in specific symbols and to a lesser degree in the placement of the symbols. No HUD has been developed in the format of either of the military specifications(96,97). While this has not been a serious problem in the past, as more and more HUDs are introduced, the lack of standardization will have an effect.

VOCABULARY

There were some difficulties encountered during the survey by the pilots misinterpreting certain terms. The terms flight path angle, roll angle, and pitch, in particular, appeared easily confused. The following terms are recommended to minimize any such confusion.

Velocity Vector

Velocity vector is used to describe the trajectory of the airplane as displayed on the HUD. It may be based on inertial data (i.e. ground based data) or on air mass data. Velocity vector includes the drift resulting from crosswinds or sideslip. The term, flight path angle (FPA) will be reserved for velocity vector with the left/right drift cancelled.

The term flight path marker appeared to be often confused with the pitch scale reference (pitch ladder).

The only potential problem with the use of velocity vector would be the abbreviation. If we abbreviate with the letters VV, confusion with vertical velocity could result.

Flight Path Angle

Flight path angle (FPA) is used to describe the caged velocity vector or the descent angle of the airplane with respect to the horizontal without any left/right component. Like the velocity vector, FPA can be inertially or air mass data derived.

Pitch Symbol

Pitch refers to an indication of the aircraft pitch attitude above or below the horizontal. It is a fixed (or pilot adjustable) reference. Care must be taken not to confuse pitch with the pitch ladder. Other terms that are used are the aircraft reference, the waterline symbol, or the aircraft (or armament) datum line. Pitch is preferred because of consistency with the head-down panel. The term "aircraft symbol" should not be used.

Pitch Ladder

The pitch ladder is the scale (calibrated in degrees) used as a background reference for velocity vector, flight path angle, or pitch and typically consists of five degree increments above and below the horizontal.

Roll Index

The roll index is a calibration scale (in degrees) used to show the actual roll angle of the airplane. It should not be confused with roll-stabilization or lack of roll-stabilization. A HUD may be roll-stabilized and still not have a roll index.

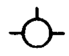
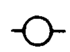
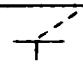
PRIMARY SYMBOLS

Unfortunately, as is well known, the subject of display symbology has at least as many expert opinions as there are pilots. Nevertheless, we strongly feel that HUD symbology should be standardized now, while there are still relatively few HUD types in service. At the very least, common symbols for velocity vector, aircraft pitch, flight director commands, and ILS deviation should be established.

We would propose the following approach to HUD standardization: (1) the choice of symbols should be based on HUDs flying today; (2) HUDs deemed "acceptable" by their pilots should be given more weight than unacceptable HUDs; (3) possible confusion with similar symbols in other HUDs should be avoided; and (4) where a choice still exists, the military standard(97) should be used.

If we follow this rationale, the choices for the preferred HUD symbols would be the winged and tailed circle for the velocity vector (used in the A-7, F-14, F-15, F-16, F-18); the winged W for aircraft pitch (used in the F-15 and F-111); and the "tadpole" for the flight director (used in the A-7 and the new F-16). The choice for the ILS deviation is not as clearcut and could be equally suitable if chosen from the perspective symbol of the A-7, the synthetic runway of the TC-121, and the limits box of the proposed DC-9-80 HUD. Table XXXI summarizes the choices of the symbols.

The fast/slow error (driven by either AIA or airspeed) has three choices, all of which seem to work (plus a fourth soon to be placed into production). They are the AOA bracket (fly-from in the A-7 and fly-to in the F-14, F-16, and F-18); the pitch/flight path angle reference of the Thomson TC-121; and the three colored lights of the MARS HUD and the VAM.

PARAMETER	SYMBOL	NUMBER OF HUDS	COMMENTS
VELOCITY VECTOR		5	Most widely used symbol; Recommended standard
		3	Has been used for pitch; Alternate standard
		3	No drift angle displayed; Recommended for flight path angle with no drift shown
		1	Can be confused with ILS deviation
		1	Has been used for flight path angle only
		1	Used in NASA simulation
		0	Military standard
FLIGHT DIRECTOR		3	Recommended standard
		3	Can be confused with ILS deviation
		1	
		1	
		1	
		0	Military standard; can be confused with ILS deviation

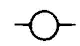
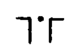
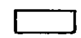
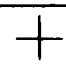
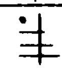
PARAMETER	SYMBOL	NUMBER OF HUDS	COMMENTS
AIRCRAFT PITCH		3	Recommended standard
		4	Easily confused with velocity vector
		3	Can be confused with ILS deviation
		1	Military standard for velocity vector
		1	
		1	Can be confused with ILS deviation
	Digital	1	Difficult to fly
		0	Military standard
ILS DEVIATION		2	Shows ILS maximum deviation limits clearly; Recommended standard
		4	Useful in contact analog display
		3	Alternate standard
		2	
		1	
		0	Military standard

TABLE 31

HUD SYMBOL STANDARDIZATION

The proposed DC-9-80 HUD will use an error symbol growing out of the velocity vector's wings. (This was originally proposed by ALPA in Reference 111.) Based on standarization, we recommend the error bracket with a fly-to sense. Although this ALPA "speed work" has the advantage of always being attached to the velocity vector, this speed symbol would be driven by angle-of-attack, if available, or by airspeed error.

SCALES

The choice of scales presentation (airspeed, altitude, etc.) is not as clear at present. There is insufficient evidence to choose between moving tape or digital presentations. The thermometer format of the A-7 does seem to be less than a complete success. Until the question of the suitability of the various scale formats is resolved, no standard should be formulated.

The heading display, however, is satisfactory as displayed on the A-7, F-14, or F-15. The combined analog/digital presentation of the F-18 may also be desirable. In addition, the heading should be displayed on a one-to-one scale, not with the compressed scales as on the AV-8 and the F-14 (in some modes).

There was also a great deal of interest in displaying a bank angle reference on the HUD. Such a reference, according to MIL-STD-884C(97), should be shown on the bottom of the HUD. The pilots also asked for selective declutter - that is the ability to show part of the scales while rejecting the rest. This is available on the AV-8 HUD at present, but other HUDs have an all or nothing choice for the scales. How to mechanize this is not clear and needs to be studied further.

OTHER DATA

Based on the responses of the pilots, additional data are sometimes desired - depending on the situation. These data parameters include additional navigational data, performance data, and systems data.

Navigational Data

Three general parameters were mentioned frequently - TACAN/VOR deviation, DME/range data, and some type of clock function. The enroute deviation, whether TACAN or VOR derived, could most easily be shown with the vertical portion of the ILS symbol. This is already widely used. To or from information could follow the pattern used in the F-14 (i.e. dashed symbol for from and solid symbol for to) unless this is not sufficient coding. The "homer" presentation of the AV-8 does not appear to be especially well liked.

A rising anticipatory cue for pull up is widely used for weapons delivery. This could be a very helpful aid for maintaining altitude awareness as the pilot approaches decision height. Such a rising cue has not been widely proposed for DH determination, but it has been used for a flare cue in the NASA simulation study.*

DME and clock functions should be shown digitally in the data box on the bottom left of the HUD, when desired. Both functions are desired in different situations. Possibly short range distances could be shown by a range circle.

Performance Information

Pilots, whether they are fighter or transport pilots, deal frequently with energy management situations. Most HUDs and panel

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* Richard Bray, NASA/Ames, personal communication, January 1980.

instruments show the aircraft's total energy (kinetic energy or airspeed plus potential energy or altitude), but not the rate of change of this energy. Several data parameters have been proposed to help the pilot keep aware of trends. Thrust is often cited by pilots. Klopfstein has proposed a "potential flight path angle," PFPA(20,81,82,83), which seems to work quite well once the symbols have been sorted out. Another tool would be airspeed trend (but not AOA trend). PFPA or total energy rate could be a useful tool for the landing approach and wind shear or engine failure case. This could be shown as an up/down symbol at the velocity vector driven by longitudinal acceleration. It would rise to show excess thrust (airplane accelerating) and fall to show a thrust deficiency. While we prefer a "whisker" growing out of the velocity vector wings, this has already been proposed for speed error. Therefore the Klopfstein format (modified with an arrowhead) is recommended.

In fighter aircraft, this arrowhead could rotate to show the need to increase or decrease speed to maintain the optimum energy airspeed/mach.

Systems Data

The pilots often desired additional systems data. These could best be shown in digital form in the data box on the lower left corner of the HUD.

Warning data were discussed by several pilots. A master warning repeater is an essential HUD feature, especially in a single place airplane. Specific warnings do not appear to be needed, although several pilots asked for fire warning repeaters or gear indicated repeaters. A mandatory pull-up (flaxhing X) should be available in all modes of flight.

The HUD mode* should be readily apparent simply by looking. Submodes* should be clearly annunciated and not rely on subtle cues - such as flashing symbols or changing display dynamics - to alert the pilot.

A frequent request in the survey was for a repeat of the radio frequency on the HUD. Such a request is unique to the single place fighter aircraft since the pilot must tune his radio by feel while maintaining his position in formation. Such data would only be required while actually tuning the radios and could best be displayed automatically whenever the pilot touched the radio tuning controls (and possibly for a few seconds thereafter). Both communication and navigation ratios should be displayed as needed.

SUMMARY

Although we are reluctant to propose an entire HUD symbology, we do feel that we should combine these cues into a package. Such a display is shown in Figure 26. Digital scales are shown for airspeed and altitude; however these may be replaced by moving tape scales (or possibly moving index scales) if they prove to be superior.

The scales should be selectable individually. The pitch ladder has been made finer for the first five degrees, at the request of several pilots, but these two-and-one-half degree pitch lines could be deleted. The roll index (not shown) would be optional at pilot discretion.

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* HUD modes might include Takeoff or Go-Around, Enroute or Navigation, or Approach or Land. Examples of submodes might be intercept, track, flare, and roll-out in the Land mode.

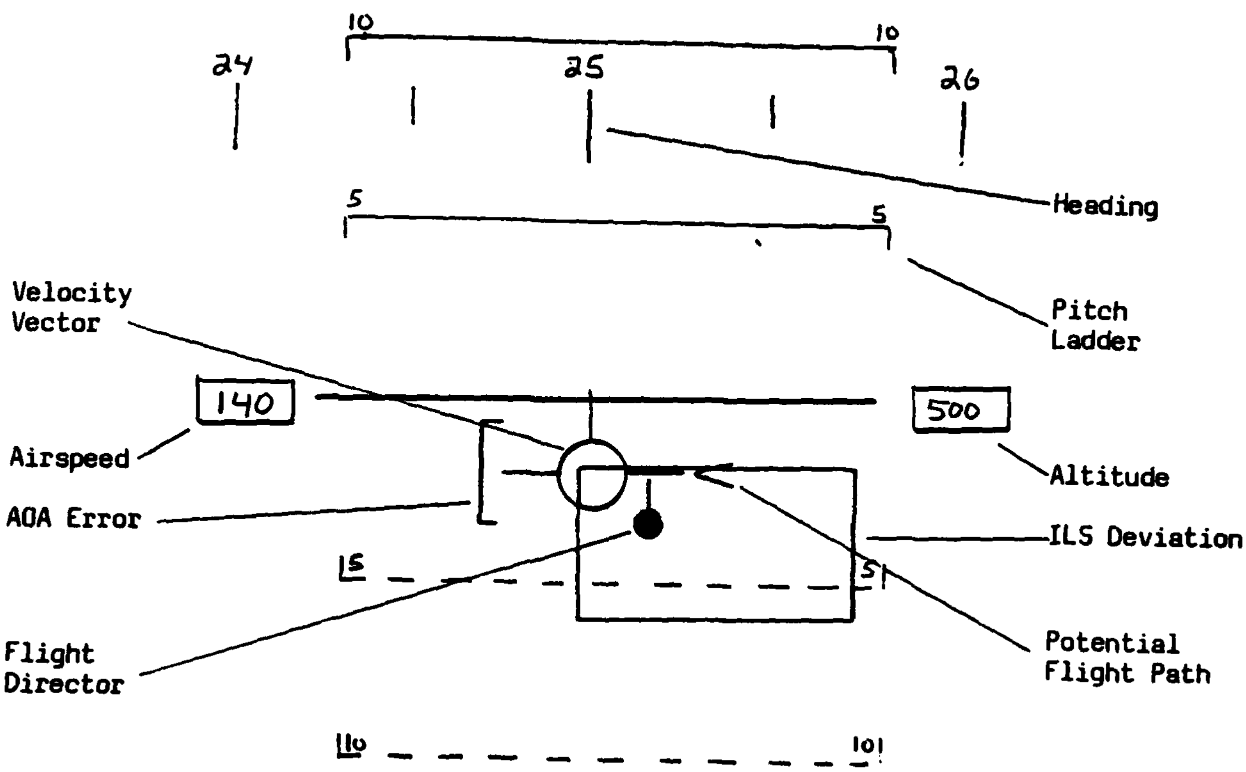

Figure 24

Proposed HUD Symbology

FORMAT FOR HUD FOLLOW-UP INTERVIEWS

One of the tasks of the present study was to develop a follow-up interview or questionnaire survey to answer any unresolved questions that remained following the intial questionnaire. During the course of this study, a draft format was prepared and several A-7D pilots from the 178th TFG were interviewed in an effort to debug the questions. The interview format was chosen to allow the pilots a freer hand in expressing their answers, but still allowing for ease of interpretations. The proposed format is attached as Appendix B.

CHOICE OF PILOTS TO BE INTERVIEWED

Because of specific problems with their HUDs, pilots of A-10 and F-111 will not be interviewed. These HUDs are not likely to be duplicated in the future and the pilots' responses will shed little light on the main issues. The F-14 HUD falls in the same category, except that the issue of compressed pitch scales is of sufficient interest to warrant including these pilots.

The pilots to be interviewed will include A-7D, AV-8, F-14, F-15, and F-16. Both old and new F-16 HUD symbologies will be covered. If possible, those transport pilots presently using HUDs to fly ILS approaches should be included.

ILS APPROACH QUESTIONS

The initial questions concern how the pilot actually uses the HUD during an ILS approach. Specific attention will be paid to the subject of altitude and position awareness and the cues used to determine proximity to the decision height (DH).

Flight director versus raw ILS deviation preference information will be asked of A-7, F-15, and F-16 pilots. The F-16 pilots will be asked to compare the "old" and the "new" F-16 displays if they have flown both. (We will attempt to interview pilots who have flown both.)

All pilots will be asked if they have experienced any illusions while flying the HUD to low minimums. If they respond affirmatively, they will be asked to elaborate.

DATA PRESENTATION QUESTIONS

The questions here are primarily concerned with the balance of needed data with clutter and the ability of the pilot to select what he needs. Various types of selective declutter options will be presented and the pilot asked to choose one. The choices are:

Scales on (full time)

Scales on or off (like the A-7)

Individual toggle switches to select each scale independently (like the AV-8)

A rotary scales switch, with positions varying from nothing to one scale to two scales to...to all scales

Automatic scales selection depending on mode or aircraft configuration

No scales at all.

The pilot will also be asked to choose an order of presentation for a rotary type scales control. Control of a pitch ladder and/or roll index will also be discussed.

The need for redundant data (i.e. velocity vector plus vertical velocity or aircraft pitch plus velocity vector) will also be addressed to obtain the pilots' input.

We will also ask the pilots their opinion as to the ease of determining the mode of operation of the HUD, the source of the data (i.e. radio versus barometric altitude), and the validity of the data.

VELOCITY VECTOR QUESTIONS

In this section we will ask the pilots to describe his control techniques for controlling the velocity vector as well as any difficulties he may have returning to a pitch reference (head-down). We will also inquire if he feels that having the velocity vector improves one's flight performance in general.

The question of lateral velocity vector motion will also be addressed.

DISORIENTATION QUESTIONS

These questions will help amplify the previous data on disorientation. This is in an effort to define just how serious the problem is. The F-14 and AV-8 pilots will be asked if the compressed pitch and heading scales help or not in flying the airplane or in reducing the tendency toward disorientation.

ADDITIONAL QUESTIONNAIRES

We also recommend additional use of the questionnaires used in this study(41). Four groups of pilots should be surveyed to improve the data base. These are operational (not test) F-16 pilots, low-time A-7E pilots, additional PWA pilots flying VAM equipped airplanes, and Air Inter Mercure pilots.

The A-7D pilots who were followed during their first 100-200 hours of HUD flying should continue to be followed until they reach 300-400 hours and become "experienced" HUD pilots.

CONCLUSIONS

OPERATIONAL PROBLEMS

A number of operational problems associated with head-up displays have been identified based on a survey of pilots presently flying HUD-equipped airplanes. These problem areas include the effect of display motion, pilot disorientation, confusing ILS displays, display brightness, and the location of the design eye reference position.

Display Motion

Many of the pilots surveyed complained about the response of the HUD symbols. While two displays were described as "backwards,"* most of the negative comments were addressed at the symbol used for primary flight control. These complaints tended to describe the motion of the velocity vector or pitch symbol as "too sensitive" or as "jitter."

While the importance of the dynamic response of the HUD symbol has been recognized in previous research(31,35,100), these research results have not yet been integrated into the display standards and specifications. The standard for electronic displays(97) only describes the velocity vector as "generally damped to make it usable." This lack of attention may reflect the difficulty of controlling this overall response with several different dynamic elements in series. In any event, the effect is that the control gains and lead/lags are based on simulation

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* The A-7 angle of attack error bracket (the only fly-from cue) and the F-15 airspeed/altitude moving tapes were described as being backwards.

evaluation. This is in spite of Hoerner's warnings that simulator results are questionnable(35).

At this point in time, insufficient data are available to identify these response characteristics that make a HUD acceptable to the pilots or make it unusable. It must be emphasized that the practice of using a static picture as a specification is quite insufficient. Both the dynamic response of each element and the relative motion within the display must be specified in order to control the quality of the HUD.

Pilot Disorientation

A significant number of pilots (approximately thirty percent) reported that the HUD tended to induce disorientation or vertigo when they were flying. The most common conditions during which disorientation was induced involved flying in-and-out of clouds. Disorientation was also reported when flying by reference to the HUD in strong crosswinds with the velocity vector displaced to one side or during pull-ups or similar maneuvers at night. All of these situations are reported to be disorienting, even without a HUD(104).

Several hypotheses have been advanced to explain this increased tendency; however none have been proven at this point. Possible explanations include conflicting cues between the HUD and the real world, motion of the background toward the pilot in clouds, visual accommodation problems, additional head movement required of the pilot, and possible lack of pilot confidence in the display. Several pilots reported that extreme lateral motion of the velocity vector had a disorienting effect during ILS approaches.

ILS Presentation

The presentation of ILS information was not desired by the pilots whose airplanes had that capability. The problems ranged from poor flight director response in the A-7 to the lateral velocity vector dynamics mentioned in the last section. Other complaints concerned the lack of raw ILS data in the F-15 HUD and the lack of roll stabilization in the F-16 HUD. The F-16 HUD is being modified to correct some of these complaints - the results of this should be interesting.

The problems of display motion, pilot disorientation, and ILS display all interact and can not be separated. One of the fundamental issues of the use of HUDs for instrument flight is the reference point for the deviation and flight director scales. This point has not been fully resolved; however it appears as if the velocity vector should be the reference. This does create a moving reference, which may prove confusing to some pilots.

Display Brightness

The most common complaint relating strictly to the optical system of the HUDs studies was that the display could not be dimmed sufficiently at night. The HUD varied from too bright to off as the intensity control was turned down.

The only complaints about insufficient brightness during daytime flying were reported by F-15 pilots. It is not clear if this is a problem with the F-15 HUD or with the air-to-air mission of the F-15.

Design Eye Reference Position

Many pilots complained that the design eye reference position was too low. This is probably a result of the common practice of fighter pilots to raise their seats to the highest possible position in order to

increase their field of view of the external world. As a result, most pilots are seated with their eyes well above the location of the exit pupil of the HUD. The F-16 had the most complaints; although the problem did not appear to be confined to any one HUD.

PROCEDURAL ISSUES

In addition to the hardware related problems discussed above, there are also several training or procedural issues that do not appear to have been properly addressed in the present use of HUDs. The pilots' initial introduction to the HUD seems to be conducted on a haphazard basis with very little attention paid to the particular problems of the HUD. The fundamental problem seems to be a lack of understanding of the particular parameters displayed on the HUD.

The HUD procedures have been developed unofficially by the pilots with little or no guidance from AFM-51-37(39) or from the aircraft flight manuals. In some cases, the procedures are not compatible with the "standard" instrument procedures because of difference between the head-down data and that shown on the HUD.

One significant problem that has not been addressed is the cross-check of the other instruments when flying with the HUD. The pilots report some concern with not being able to detect instrument or aircraft problems while using the HUD as their sole flight reference. Some work has been done in simulation studies to determine if a pilot can detect differences between the HUD and the real world and then if he can disregard the HUD and follow the real world cues. The results of the simulation studies indicate that the pilot will disregard the HUD and fly the runway cues to a landing. This does not agree with in-flight observations

during the mid-air retrieval system HUD evaluation where the pilots followed the HUD and disregarded the real world cues (some of which were illusions and some of which were valid). This issue must be resolved before the HUD can be considered to be a primary flight reference.

USE OF HUD IN TRAINING

It was suggested that the HUD might be a very helpful tool during undergraduate pilot training (UPT) to demonstrate certain concepts that are otherwise difficult to show the student pilot. Most of the pilots surveyed felt that the HUD would be of help in UPT. Concern was expressed over the student becoming overdependent on the HUD. Surprisingly, the more experienced pilots favored this application of the HUD compared with the less experienced pilots.

It has been reported elsewhere(109) that having had prior HUD experience with the A-7 HUD makes the pilot more proficient because of increased awareness of the relationships between flight path angle, aircraft pitch, angle-of-attack, etc. Although the study reported was an informal one; if true, then the use of a HUD would be very beneficial in pilot training. Furthermore, the question of overdependence on the HUD would not apply since the student would actually have the opposite tendency.

APPROACHES TO THE DYNAMICS ISSUE

We have already indicated that the question of display dynamics (or display motion) is a fundamental one to the future of HUDs. This issue includes reference to the related ones of pilot disorientation and ILS problems. Questions of the required accuracy of HUD symbols and the need

for inertial navigation equipment also would be included in this area. These issues can not easily be separated.

How can these questions best be resolved? The use of ground based simulation has limitations. It is very difficult to separate the motion cues from the HUD and external world cues. Using a simulator alone for this type of a HUD study would cast doubt on the credibility because of uncertainties over the accuracy of the motion and external world visual cues. We agree with Hoerner(35) who feels that the only vehicle for control-display studies is an airplane in-flight. That is not to say that preliminary work cannot be done in a simulator with in-flight validation of the results.

A first step in defining the problem is to obtain the dynamic response data for airplane and HUD. Since the data do not appear to be in readily available sources (and may not be available at all), the logical approach is to measure the responses in actual airplanes. In particular, we would recommend measuring the responses to control stick inputs for both acceptable airplanes (A-7, F-15) and unacceptable airplanes (F-14, F-16). Any correlation between acceptable and unacceptable airplane/HUD combinations and the measured responses would confirm the problem.

A second approach to such a problem would be to duplicate the aircraft and HUD behavior in the AFFDL NT-33A with the Navy Display Evaluation Flight Test (DEFT) programmable HUD. By duplicating an "acceptable" aircraft/HUD combination and then de-tuning the responses, a more controlled description of the boundaries between "good" and "bad" characteristics could be obtained. Use of the NT-33 would also allow us to check for the effects of display accuracy since the response of the HUD could

be controlled to allow for subtle mismatches with the real world. The differences between air mass data and inertial data could also be studied.

A final approach would be to use an existing acceptable HUD, preferably in a two seat version and selectively degrade the HUD. This could be done by disabling the inertial system, for example.

Clearly, the best approach from a technical point of view is the use of a variable stability/variable HUD airplane, such as the NT-33. From a cost-effectiveness point of view, one of the other approaches might be mcre beneficial. The NT-33 could also be used to develop and validate HUD training curricula and to measure pilot susceptibility to spatial disorientation.

NEED FOR STANDARDIZATION

The final conclusion reached during this study was the need to standardize HUDs now. There appear to be almost as many HUD formats as there are people who have heard of HUDs. An approach to HUD standardization has been taken based on making the maximum use of existing HUDs which have been well received by their pilots. The best features of these HUDs have been incorporated into a tentative standardized HUD format.

RECOMMENDATIONS

The following areas are recommended for further work.

IMPROVE HUD DATA BASE

Follow-Up Interviews

We should continue to define the extent of the problem by conducting interviews with representative pilots flying HUD-equipped airplanes. These interviews would follow the format of Appendix B and would include pilots flying A-7, AV-8, F-14, F-15, and F-16 airplanes. Pilots flying civil transports equipped with HUD landing aids should also be interviewed.

Additional Questionnaires

At the same time, additional responses to the initial questionnaire (Appendix A) from certain pilots would greatly enhance the coverage of HUD pilots. These selected pilots are operational (not test) F-16 pilots, low-time A-7E pilots, and civil transport pilots. These selected pilots should be surveyed and their reqponses included in the data of this report.

Continue Training Review

The monitoring of the A-7D pilots during their first year should be continued until their responses indicate steady-state behavior. This point is projected to be reached at approximately 300 hours of A-7D flying time.

DEVELOP DYNAMIC CORRELATION

Obtain Dynamic Response Data

The dynamic response of existing airplane/HUD combinations should be obtained. If possible, this should be done by using existing flight test records from the Air Force Flight Test Center (Edwards AFB) or from the Naval Air Test Center (Patuxent River NAS). If these data are not available, then they should be obtained from in-flight measurements using service aircraft. These data should be limited to those few HUD/airplanes where the HUD is clearly acceptable (A-7 or F-15) and to those HUD/airplanes where the HUD response is clearly unacceptable (F-14, F-16).

Using these data, we should determine if a correlation exists between these airplane/HUD responses and pilot ratings.

Experiment to Evaluate Response

An experiment to evaluate permutations in dynamic HUD response should be developed using the NT-33 DEFT airplane or an existing HUD-equipped airplane. The NT-33 would allow variations in both aircraft and HUD responses. The use of an existing HUD-equipped airplane would permit the variation of HUD responses only. If the existing aircraft approach is used, a "good" airplane/HUD should be used and degraded to the point of its unacceptability. This would allow us to determine the envelope of HUD/airplane responses that results in acceptable pilot ratings.

Definition of Accuracy Requirements

A flight experiment to define the accuracy requirements of HUDs and the differences between inertially-derived and air-mass-derived velocity vectors should be developed and then conducted. The results of such an experiment would allow the Air Force to better define the HUD

specifications. This experiment should be developed in conjunction with the previous experiment aimed at developing dynamic correlations.

MEASURE THE PILOT'S ABILITY TO DETECT HUD DISCREPANCIES

Instrument Errors in Solid IMC

An experiment must be developed to determine how well a pilot can detect insidious HUD or instrument errors while flying with reference to the HUD. Such a study would be based on flight in solid instrument conditions and could be accomplished in a simulator.

Pilot Reaction to Subtle HUD Errors

A second experiment should be conducted to determine the pilot's reaction to subtle HUD errors or real world visual illusions. This could be conducted in a simulator on in-flight - although it must be validated by an in-flight experiment. The previous HUD simulations of this problem only considered misalignments in a horizontal direction. The recommended experiment must also consider the vertical illusions caused by sloping terrain, black-hole runways, or reduced visual segments during a low visibility approach.

In addition, all of the previous simulations assumed that any error would be caused by the HUD. We are recommending that visual illusions be introduced along with HUD errors. The earlier studies also used subject pilots who were naive with respect to HUD usage. We recommend that pilots with extensive HUD experience be included in the subject population.

Pilot Detection of Gross Problems

Finally, the MARS HUD studies indicate that a well-trained pilot with a HUD may react differently from a pilot flying an airplane or a

simulator with an experimental HUD. For this reason, the runway incursion study reported by NASA should be repeated with pilots who are quite experienced with the HUD they are using in the experiment. The results of the NASA study are quite disturbing to potential users of a HUD. We should repeat the experiment in an existing A-7 simulator with experienced A-7 pilots.

EVALUATE THE EFFECT OF A HUD IN SPATIAL DISORIENTATION

A flight experiment (using the NT-33) should be developed to determine the effects of various HUD characteristics (gains, accuracy, motion, etc.) on inducing or preventing pilot disorientation. This experiment should be developed in conjunction with the previously discussed experiments involving accuracy requirements and display responses.

DEVELOP HUD TRAINING PROGRAM

Effect of HUD Experience

Earlier we repeated a conclusion (reported elsewhere) that a HUD-experienced pilot shows better performance than a pilot with no HUD experience even when both pilots are flying without a HUD. This result must be confirmed and, if possible, measured. Such a result has definite implications on the possible application of HUDs to undergraduate pilot training.

Develop HUD Syllabi

Following the confirmation/rejection of the hypothesis that having previous HUD experience makes one a better pilot, the need for developing an undergraduate pilot training (UPT) syllabus with a HUD could become obvious or it would not be. Such a syllabus should be developed in

conjunction with AFHRL using a simulator to develop the program and validating it in-flight with a HUD-equipped trainer.

The proposed curricula for conducting initial check-outs in HUD-equipped airplanes should also be developed with the use of HUD part-task trainers, video tape recorders, and instructor control of the HUD. Procedures to use the HUD in-flight should also be developed. Normally the Air Force Instrument Flight Center should have performed this task. However, since its closing, no one has the responsibility. Nevertheless, it should still be done. Either an amendment to AFM-51-37(39) or a supplement should be prepared.

MODIFICATIONS TO HUD SPECIFICATIONS

The specifications for future HUDs should be improved. Clearly, some improvements will have to wait for the completion of some of the previously recommended work. However, some areas can be addressed now.

Location of Design Eye Reference Point

The location of the design ERP must take into account the seating position of the pilot in combat. Normally, the pilot will sit as high as possible, not sit at the mid-point of seat travel.

Minimum Brightness Level

The minimum level of brightness should also be specified. This level should be set lower than the level available on present HUDs.

Standardization

Finally, the subject of HUD standardization should be pursued. Clearly, this task will require coordination with a large number of organizations. Nevertheless, it should be begun now, not after many more HUD models are introduced.

OPERATIONAL PROBLEMS ASSOCIATED WITH

HEAD-UP DISPLAYS

DURING INSTRUMENT FLIGHT

APPENDIX A

HEAD-UP DISPLAY QUESTIONNAIRE

HEAD-UP DISPLAY QUESTIONNAIRE

1. What type aircraft and HUD are you presently flying?

   Aircraft________________ HUD__________________

2. What are your present flight qualifications (Instructor Pilot, Aircraft Commander, Copilot, etc.)?

3. Indicate your flight experience.

	ALL AIRCRAFT	CURRENT AIRCRAFT
Total Flying Time	____________	______________
Time as Instructor	____________	______________
Actual Instrument	____________	______________
Time Spent Using HUD	____________	______________

4. What problems have you encountered when using the HUD in the following weather conditions?

   Solid Instruments:

   In and out of clouds:

   Clear weather -- Days:

   Clear weather -- Nights:

5. How do you routinely use the HUD under the following weather conditions and phases of flight? (If you use the HUD differently at night, please show this by an "N" or a "D".)

Weather: Solid Instruments

Phase of Flight	HUD is primary flight reference	HUD used, but not primary	Occasional check	Not used
Climb				
Cruise				
Descent				
Instrument Approach				
Landing				
Go-Around				

Weather: In-and-Out of Clouds

Phase of Flight	HUD is primary flight reference	HUD used, but not primary	Occasional check	Not used
Climb				
Cruise				
Descent				
Instrument Approach				
Landing				
Go-Around				

Weather: Clear

Phase of Flight	HUD is primary flight reference	HUD used, but not primary	Occasional check	Not used
Climb				
Cruise				
Descent				
Final Approach				
Landing				
Go-Around				

6. If one data display had to be deleted from your aircraft's HUD, which would you choose?

7. If one additional data display could be added to your aircraft's HUD, what would you choose?

8. Do you feel that the HUD is ( ) more reliable than panel instruments?
( ) equally reliable?
( ) less reliable?

9. Do you feel that the HUD is ( ) more accurate than panel instruments?
( ) equally accurate?
( ) less accurate?

10. Are there any format problems, such as distracting symbology, poor sensitivity, "backwards" cues, distortions, etc.?

If so, please describe.

11. Does the velocity vector (flight path marker) always line up over the runway on approaches?

Does this cause any problems during routine instrument flight?

12. Have you noticed any tendency toward vertigo or disorientation?

If so, please describe.

13. Has the HUD produced any eye discomfort? If so, please describe.

14. Is the brightness control adequate for all weather conditions?

15. Can you control the brightness to make the entire display comfortable to use?

16. Is the HUD ever too cluttered?

17. Was your initial HUD training adequate?

18. What changes would you recommend?

19. Are the published procedures (flight manuals, operating manuals) adequate and appropriate for HUD flying in all weather conditions?

20. What changes would you recommend?

21. Do you feel that a good all-purpose HUD would help in primary flight training or in initial checkout in a new airplane?

22. Have you flown other HUD-equipped airplanes? If not, please skip to next page.

23. What aircraft/HUD?

24. Which HUD would you prefer for routine instrument flying?

Why?

25. Did having previous HUD experience help or hinder your adapting to a new HUD?

26. Please check the items that you feel should be included for a general purpose HUD for your type of operations.

Data Item	Needed for HUD	Comments on Presentation
Airspeed	( )	
Angle-of-attack	( )	
Altitude (barometric)	( )	
Altitude (radar)	( )	
Pitch attitude	( )	
Flight path angle (velocity vector)	( )	
Vertical velocity (rate-of-climb)	( )	
Sideslip	( )	
Roll angle	( )	
Localizer deviation	( )	
Glideslope deviation	( )	
Enroute navigation data (VOR, TACAN, etc.)	( )	
DME	( )	
Flight director commands	( )	
Power/thrust	( )	
Instrument comparator	( )	
Master warning/caution	( )	
Other		
____________________	( )	
____________________	( )	
____________________	( )	

27. Any other comments, remarks, questions, or criticism?

OPERATIONAL PROBLEMS ASSOCIATED WITH

HEAD-UP DISPLAYS

DURING INSTRUMENT FLIGHT

APPENDIX B

FORMAT FOR HUD FOLLOW-UP INTERVIEWS

The attached papges list the questions planned for the follow-up interviews to resolve questions that arose out of the questionnaire survey. These questions are grouped by the following topics:

The pilots to be interviewed will be drawn from those now flying A-7D/E, F-14, F-15, F-16, and AV-8 airplanes. If possible, civilian pilots using HUDs to fly category 3 ILS approaches will be interviewed as well.

Since the data will be gathered in interviews, it is not necessary to specify the answer format at this time.

ILS QUESTIONS (A-7, F-14, F-15, F-16 and civil HUDs)

0 During an ILS approach to minimums
in weather, please compare HUD flight
with "conventional" instrument flight.

- o Ease of flight
  - interception
  - ILS tracking
  - transition to landing
  - transition to go-around
- o Altitude awareness
- o Position awareness

0 How do you configure the HUD for an ILS
approach (scales, mode, etc.)
- interception
- ILS tracking
- transition to landing
- transition to go-around

0 What cues do you use for minimums?

0 Have you ever experienced discrepancies
between HUD and real world at minimums?
If so, please describe.

- o What did you do?

0 Would a flight director help? (F-16)

0 Would raw ILS data help? (F-15)

0 Does the flight director "tadpole"
help or hinder the ILS approach?(A-7, new F-16)

- o Would an optional Flight director
be of any merit?

0 Did the HUD changes help the ILS approach
problems? (New F-16)

0 With what minimums would you feel comfortable?

- o No HUD
- o with HUD
- o HUD only

0 How many ILS approaches have you made
in the last six months?

- o Total
- o Weather (below 500 ft)
- o Simulator

DATA PRESENTATION QUESTIONS All Multipurpose HUDs

O Are the HUD controls easy to use?
 too many controls
 location
 operation
 too frequent operation

O Scales

- o Can you always get the proper balance of needed data without clutter?

- o If given a choice for scales control, which of the following would you prefer?
 scales on, all the time
 scales switch (like A-7)
 individual switches (like AV-8)
 a rotary scales switch, from nothing to one scale to two scales ... to all scales
 preprogrammed scales depending on aircraft configuration (like F-15, gear down gives AOA)
 no scales at all

- o Consider the following scales choices:
 HEADING
 AIRSPEED
 VERTICAL VELOCITY
 ALTITUDE

 We are going to give you a rotary scales switch that will range from "no scales" to "all scales." Your HUD displays VELOCITY VECTOR and AOA full time.
 Please order the scales:
 Pos. 1 Scales off
 2
 3
 4
 5
 6 All scales on.

O Your airplane displays VELOCITY VECTOR as well as a PITCH MARKER. (F-14, F-15)

- o Do you use both?

- o Can we eliminate one (which one)?

O Your airplane displays VELOCITY VECTOR as well as VERTICAL VELOCITY. (A-7, F-14)

- o Do you use both?

- o Can we eliminate one (which one)?

DATA PRESENTATION QUESTIONS (continued)

O Your airplane displays AIRSPEED as well as ANGLE-OF-ATTACK. (A-7, F-15, F-16)

- o Do you use both?
- o Can we eliminate one (which one)?

O Can you readily determine (by looking at the HUD), the following

- o Mode
- o Source of data
  - radio versus baro altitude
  - indicated versus other airspeed (including Mach)
- o Caged velocity vector (F-15)
- o Bad data

O Are the following parameters easy to read and use?

- o AIRSPEED
- o HEADING
- o ALTITUDE
- o VERTICAL VELOCITY
- o ANGLE-OF-ATTACK
- o ILS DEVIATION

O Are the digital data boxes useful? (F-15, F-16)

O Would a second declutter switch to eliminate the pitch ladder be of value?

- o Add a roll index?
- o Change the pitch ladder intervals?

VELOCITY VECTOR QUESTIONS All HUD with a VELOCITY VECTOR

O How do you control the VELOCITY VECTOR in flight?
    stick vs. throttle

- o Do you need the fixed aircraft reticle? (F-15)
- o Do you need VERTICAL VELOCITY?

O Have you developed any new techniques to use VELOCITY VECTOR?

- o Were the original procedures clear?
- o Did they work?

O Is it difficult to shift back to a basic PITCH reference (head down) now?

O Has having a HUD with a VELOCITY VECTOR improved your flying in general?

- o Do you think that it has helped your flying without the HUD being on?
- o It has been suggested that having a VELOCITY VECTOR helps pilots fly better even after it has been taken away. Do you agree?
- o If so, would a HUD be of benefit in UPT?
    as a demonstration of principles only
    as a lead-in to tactical aircraft in general

O Is lateral VELOCITY VECTOR motion bothersome?

- o Does it cover the scales?
    should scales move with VV?
- o Is the dynamic response OK?
- o Should a cage option be provided?
    does this help?
    can you tell when caged by looking?

DISORIENTATION QUESTIONS All HUDs

O What effect does the background have on using the HUD? Consider confusing cues, disorientation, lost HUD data, lost real world data, etc.

- terrain
  - desert
  - vegatation
  - snow
- water
- clouds (in background)
- clear sky
- rain on windshield
- solid weather
- night
  - no lights
  - lights

O Are rapidly changing backgrounds significant?

- in-and-out
- air-to-ground

O During ACM or unusual positions, does the HUD data keep up with the background?

O How well can you use the compressed pitch or heading scales? (AV-8, F-14)

  o Would you prefer one-to-one scales?

O Does the HUD tend to reduce or increase disorientation or vertigo?

OPERATIONAL PROBLEMS ASSOCIATED WITH

HEAD-UP DISPLAYS

DURING INSTRUMENT FLIGHT

APPENDIX C

HEAD-UP DISPLAY BIBLIOGRAPHY

HEAD-UP DISPLAY BIBLIOGRAPHY

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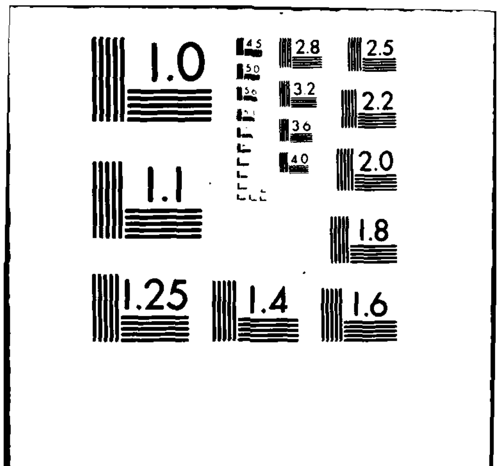

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